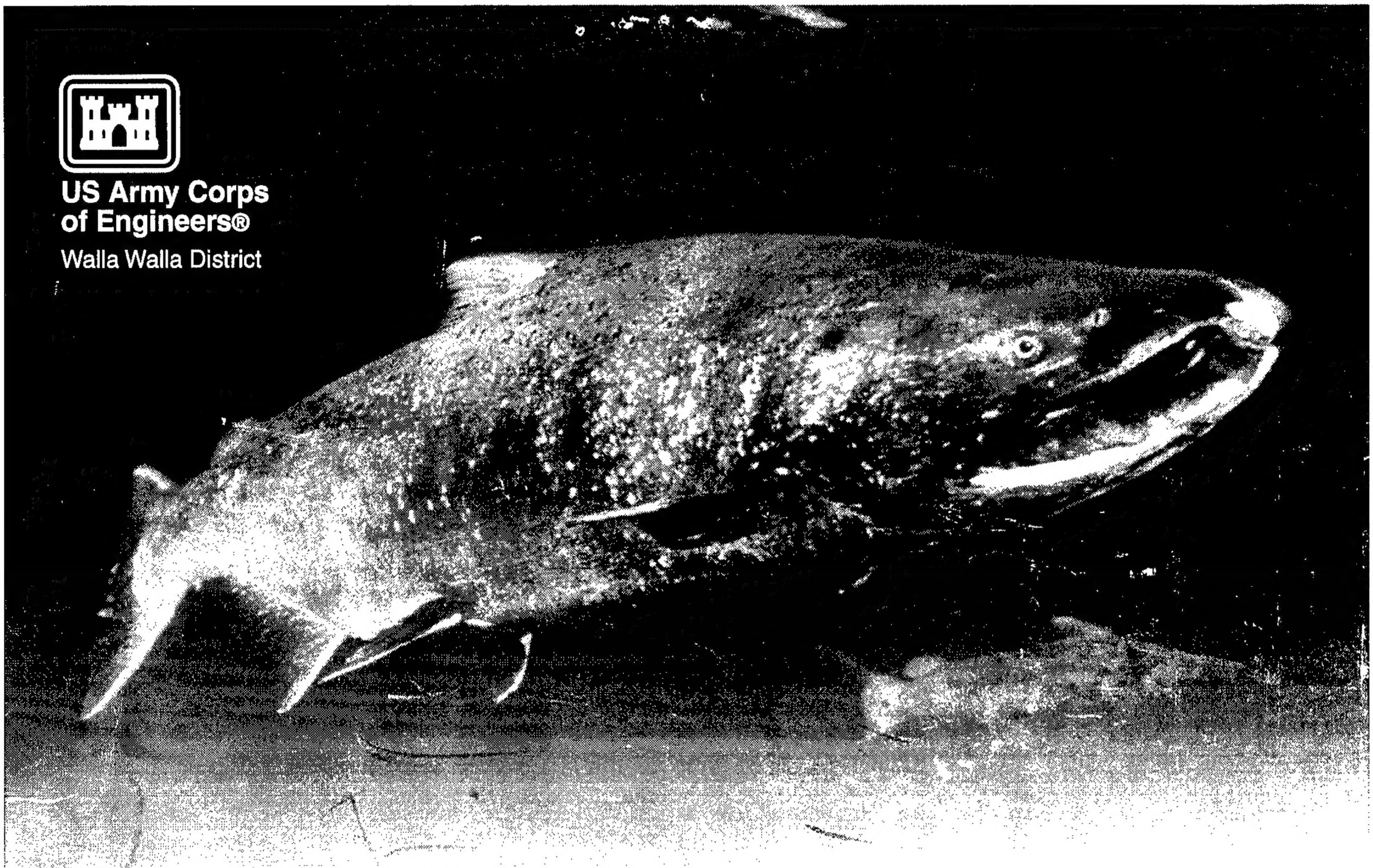

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Lower Snake River Juvenile Salmon Migration Feasibility Report/ Environmental Impact Statement

APPENDIX H
Fluvial Geomorphology

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December 1999

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The Corps of Engineers along with the Bonneville Power Administration, US Environmental Protection Agency, and US Bureau of Reclamation as cooperating agencies, analyzed four general alternatives intended to provide information on the technical, environmental, and economic effects of actions related to improving juvenile salmon passage. The four alternatives include Alternative 1 - Existing Conditions (the no-action alternative) and three different ways to further improve juvenile salmon passage. The action alternatives are: Alternative 2 - Maximum Transport of Juvenile Salmon, Alternative 3 - Major System Improvements, and Alternative 4 - Dam Breaching. Comparison of the alternatives by all of the factors assessed in the study has not offered a clear-cut recommendation at this time. It is the Corps of Engineer's intent to recommend a preferred plan of action in the Final FR/EIS.

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Summary to the Lower Snake River Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement	
Lower Snake River Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement	
Appendix A	Anadromous Fish
Appendix B	Resident Fish
Appendix C	Water Quality
Appendix D	Dam Breaching Engineering
Appendix E	Existing Systems and Major System Improvements Engineering
Appendix F	Hydrology/Hydraulics and Sedimentation
Appendix G	Hydroregulations
Appendix H	Fluvial Geomorphology
Appendix I	Economics
Appendix J	Plan Formulation
Appendix K	Real Estate
Appendix L	Lower Snake River Mitigation History and Status
Appendix M	Fish and Wildlife Coordination Act Report
Appendix N	Cultural Resources
Appendix O	Public Outreach Program
Appendix P	Air Quality
Appendix Q	Tribal Consultation/Coordination
Appendix R	Historical Perspectives
Appendix S	Snake River Maps
Appendix T	Biological Assessment
Appendix U	Clean Water Act, Section 404(b)(1) Evaluation

The documents listed above, as well as supporting technical reports and other study information, are available on our website at www.nww.usace.army.mil. Copies of these documents are also available for public review at various city, county, and regional libraries.

FOREWORD

This appendix is one part of the overall effort of the U.S. Army Corps of Engineers (Corps) to prepare the Lower Snake River Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement (FR/EIS).

Please note that this document is a DRAFT appendix and is subject to change and/or revision based on information received through comments, hearings, workshops, etc. After the comment period ends and hearings conclude a Final FR/EIS with Appendices is planned.

The Corps has reached out to regional stakeholders (Federal agencies, tribes, states, local governmental entities, organizations, and individuals) during the development of the FR/EIS and appendices. This effort resulted in many of these regional stakeholders providing input, comments, and even drafting work products or portions of these documents. This regional input provided the Corps with an insight and perspective not found in previous processes. A great deal of this information was subsequently included in the Draft FR/EIS and Appendices, therefore, not all the opinions and/or findings herein may reflect the official policy or position of the Corps.

STUDY OVERVIEW

Purpose and Need

Between 1991 and 1997, due to declines in abundance, the National Marine Fisheries Service (NMFS) made the following listings of Snake River salmon or steelhead under the Endangered Species Act (ESA) as amended:

- sockeye salmon (listed as endangered in 1991)
- spring/summer chinook salmon (listed as threatened in 1992)
- fall chinook salmon (listed as threatened in 1992)
- steelhead (listed as threatened in 1997)

In 1995, NMFS issued a Biological Opinion on operations of the Federal Columbia River Power System. The Biological Opinion established measures to halt and reverse the declines of these listed species. This created the need to evaluate the feasibility, design, and engineering work for these measures.

The U.S. Army Corps of Engineers (Corps) implemented a study after NMFS's Biological Opinion in 1995 of alternatives associated with lower Snake River dams and reservoirs. This study was named the Lower Snake River Juvenile Salmon Migration Feasibility Study (Feasibility Study). The specific purpose and need of the Feasibility Study is to evaluate and screen structural alternatives that may increase survival of juvenile anadromous fish through the Lower Snake River Project (which includes the four lowermost dams operated by the Corps on the Snake River—Ice Harbor, Lower Monumental, Little Goose, and Lower Granite dams) and assist in their recovery.

Development of Alternatives

The Corps completed an interim report on the Feasibility Study in December 1996. The report evaluated the feasibility of drawdown to natural river levels, spillway crest, and other improvements to existing fish passage facilities. Based in part on a screening of actions conducted in the interim report, the study now focuses on four courses of action:

- Existing conditions (currently planned fish programs)
- System improvements with maximum collection and transport of juveniles (without major system improvements such as surface bypass collectors)
- System improvements with maximum collection and transport of juveniles (with major system improvements such as surface bypass collectors)
- Dam breaching or permanent drawdown to natural river levels for all reservoirs

The results of these evaluations are presented in the combined Feasibility Report (FR) and Environmental Impact Statement (EIS). The FR/EIS provides the support for recommendations that will be made regarding decisions on future actions on the Lower Snake River Project for passage of juvenile salmonids. This appendix is a part of the FR/EIS.

Geographic Scope

The geographic area covered by the FR/EIS generally encompasses the 140-mile long lower Snake River reach between Lewiston, Idaho and the Tri-Cities in Washington. The study area does slightly vary by resource area in the FR/EIS because the affected resources have widely varying spatial characteristics throughout the lower Snake River system. For example, socioeconomic effects of a permanent drawdown could be felt throughout the whole Columbia River Basin region with the most effects taking place in the counties of southwest Washington. In contrast, effects on vegetation along the reservoirs would be confined to much smaller areas.

Identification of Alternatives

Since 1995, numerous alternatives have been identified and evaluated. Over time, the alternatives have been assigned numbers and letters that serve as unique identifiers. However, different study groups have sometimes used slightly different numbering or lettering schemes and this has lead to some confusion when viewing all the work products prepared during this long period. The primary alternatives that are carried forward in the FR/EIS currently involve four major alternatives that were derived out of three major pathways. The four alternatives are:

Alternative Name	PATH[1/] Number	Corps Number	FR/EIS Number
Existing Conditions	A-1	A-1	1
Maximum Transport of Juvenile Salmon	A-2	A-2a	2
Major System Improvements	A-2'	A-2c	3
Dam Breaching	A-3	A-3a	4

[1/] Plan for Analyzing and Testing Hypotheses

Summary of Alternatives

The **Existing Conditions Alternative** consists of continuing the fish passage facilities and project operations that were in place or under development at the time this Feasibility Study was initiated. The existing programs and plans underway would continue. Project operations, including all ancillary facilities such as fish hatcheries and Habitat Management Units (HMUs) under the Lower Snake River Fish and Wildlife Compensation Plan (Comp Plan), recreation facilities, power generation, navigation, and irrigation would remain the same unless modified through future actions. Adult and juvenile fish passage facilities would continue to operate.

The **Maximum Transport of Juvenile Salmon Alternative** would include all of the existing or planned structural and operational configurations from the Existing Conditions Alternative. However, this alternative assumes that the juvenile fishway systems would be operated to maximize fish transport from Lower Granite, Little Goose, and Lower Monumental and that voluntary spill would not be used to bypass fish through the spillways (except at Ice Harbor). To accommodate this maximization of transport some measures would be taken to upgrade and improve fish handling facilities.

The **Major System Improvements Alternative** would provide additional improvements to what is considered under the Existing Conditions Alternative. These improvements would be focused on using surface bypass collection (SBC) facilities in conjunction with extended submersible bar screens (ESBS) and a behavioral guidance system (BGS). The intent of these facilities is to provide more effective diversion of juvenile fish away from the turbines. Under this alternative the number of fish collected and delivered to upgraded transportation facilities would be maximized at Lower Granite, the most upstream dam, where up to 90 percent of the fish would be collected and transported.

The **Dam Breaching Alternative** has been referred to as the "Drawdown Alternative" in many of the study groups since late 1996 and the resulting FR/EIS reports. These two terms essentially refer to the same set of actions. Because the term drawdown can refer to many types of drawdown, the term dam breaching was created to describe the action behind the alternative. The Dam Breaching Alternative would involve significant structural modifications at the four lower Snake River dams allowing the reservoirs to be drained and resulting in a free-flowing river that would remain unimpounded. Dam breaching would involve removing the earthen embankment sections of the four dams and then developing a channel around the powerhouses, spillways, and navigation locks. With dam breaching, the navigation locks would no longer be operational, and navigation for large commercial vessels would be eliminated. Some recreation facilities would close while others would be modified and new facilities could be built in the future. The operation and maintenance of fish hatcheries and Habitat Management Units (HMUs) would also change although the extent of change would probably be small and is not known at this time. Project development, design, and construction span a period of nine years. The first three to four years concentrate on the engineering and design processes. The embankments of the four dams are breached during two construction seasons at year 4-5 in the process. Construction work dealing with mitigation and restoration of various facilities adjacent to the reservoirs follows dam breaching for three to four years.

Authority

The four Corps dams of the lower Snake River were constructed and are operated and maintained under laws that may be grouped into three categories: 1) laws initially authorizing construction of the project, 2) laws specific to the project passed subsequent to construction, and 3) laws that generally apply to all Corps reservoirs.

BOUNDARIES

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GEOGRAPHIC INFORMATION SYSTEMS

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Walla Walla District

1 : 1,900,800

DRAFT

Lower Snake River

Juvenile Salmon Migration Feasibility Study

REGIONAL BASE MAP

1999

GIS Analysis & Graphic Assembly: Applied Technology Team (CENWW-PM-PD-E)
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ABSTRACT

This report is Appendix H, Fluvial Geomorphology, to the Lower Snake River Juvenile Migration Feasibility Report/Environmental Impact Statement. The Pacific Northwest National Laboratory prepared the appendix. Evaluation of the response of Snake River salmonids to altered flow conditions resulting from drawdown scenarios has been largely based on the results of salmon passage models and life-cycle models. These models indicate that juvenile migration timing and survival are influenced by water velocity and discharge volume. Changes in physical channel characteristics (i.e., geomorphological changes) and habitat resulting from drawdown scenarios have not received much attention. This document includes two related reports that represent a compilation of ongoing work on physical characteristics and riverine processes of the lower Snake River. Part 1 provides an assessment of restoring pre-dam channel morphology, salmonid habitats, and riverine processes through drawdown. Part 2 describes sediment transport processes as estimated through the use of hydrodynamic modeling.

US Army Corps
of Engineers®
Walla Walla District

Draft
Lower Snake River Juvenile Salmon Migration Feasibility Report/ Environmental Impact Statement

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Appendix H
Fluvial Geomorphology

Produced by
Pacific Northwest National Laboratory

Produced for
U.S. Army Corps of Engineers
Walla Walla District

Completed December 1999
Revised and released for review
with Draft FR/EIS
December 1999

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ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
AEI	Agricultural Enterprises, Inc.
AGU	American Geophysical Union
ANCOOR	Analytical Coordination Workgroup
ASCE	American Society of Civil Engineers
BA	Biological Assessment
BOR	Bureau of Reclamation
BPA	Bonneville Power Administration
CCC	Civilian Conservation Corps
CEQ	Council on Environmental Quality
cfs	cubic feet per second
Corps	U.S. Army Corps of Engineers
DEM	digital elevation model
DGAS	Dissolved Gas Abatement Study
DREW	Drawdown Regional Economic Workgroup
EIS	environmental impact statement
ESA	Endangered Species Act
FCRPS	Federal Columbia River Power System
Feasibility Study	Lower Snake River Juvenile Salmon Migration Feasibility Study
FR	Federal Register
GIS	Geographic Information System
IDFG	Idaho Department of Fish and Game
IDFG v. NMFS	Idaho Department of Fish and Game v. Natural Marine Fisheries Service
ISG	Independent Scientific Group
MASS1	Modular Aquatic Simulation System 1D
MASS2	Modular Aquatic Simulation System 2D
M&I	municipal and industrial
MOA	Memorandum of Agreement
MOP	minimum operating pool
NED	national economic development
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NPPC	Northwest Power Planning Council
NWPPC	Northwest Power Planning Council
OA/EIS	Columbia River Salmon Flow Measures Options Analysis/Environmental Impact Statement
P	river sinuosity
PATH	Process for Analyzing and Testing Hypotheses
PNCA	Pacific Northwest Coordination Agreement
PNW RRF	Pacific Northwest River Reach Files
RKM	River Kilometer
RM	River Mile

ACRONYMS AND ABBREVIATIONS

ROD	Record of Decision
SCS	System Configuration Study
SEIS	Supplemental Environmental Impact Statement
SOR	System Operation Review
SOS	System Operating Strategies
SRSRT	Snake River Salmon Recovery Team
TAG	Technical Advisory Group
USGS	United States Geological Survey
USFWS	U.S. Fish and Wildlife Service
WPPSS	Washington Public Power Supply System
WSCC	Western States Coordinating Council

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Executive Summary

Background

Four dams on the lower Snake River have created a nearly continuous reservoir system, reducing the availability of riverine habitat and impacting life history strategies for all populations of Snake River salmonids. Snake River populations of salmon and steelhead have declined during the past 30+ years. As a result, National Marine Fisheries Services (NMFS) listed several species of salmon and steelhead as threatened or endangered under the Endangered Species Act (ESA). In 1995, NMFS issued a Biological Opinion calling for an evaluation of structural and operational modifications to the four hydroelectric dams operated by the U.S. Army Corps of Engineers (Corps) on the lower Snake River. The Lower Snake River Juvenile Salmon Migration Feasibility Study—Interim Status Report was released in 1995 as a result of this action. Of the drawdown scenarios considered in the Interim Status Report (e.g., seasonal, yearlong, variable discharges, variable elevation), only permanent drawdown is currently being evaluated. This alternative entails the breaching of the earthen portion of each of the four lower Snake River dams (Ice Harbor, Lower Monumental, Little Goose, and Lower Granite). The Independent Scientific Group of the Northwest Power Planning Council (NPPC) and NMFS have suggested that breaching the four lower Snake River dams could be beneficial not only to migrating juvenile salmonids, but also to those salmonids that spawn and rear in the mainstem Snake River (e.g., fall chinook salmon and steelhead trout).

Objectives

The investigation of channel morphology (Part 1 of this Appendix H) set out to address the question, "To what extent can mainstem habitats and riverine processes required for salmon production be achieved by near-dam breaching?" The first objective was to describe the physical characteristics and habitats of the pre-dam river. The second objective was to quantify the geomorphic features that describe salmon production areas. The third objective was to evaluate changes in the flow regime under near-dam breaching.

The objectives of the hydrodynamic modeling (Part 2 of this Appendix H) were to compare hydraulic conditions and sediment mobility in the lower Snake River for current and natural river conditions using mathematical models of the river system.

Approach

The study area extended from the mouth of the Snake River near Pasco, Washington, at the confluence with the Columbia River, to River Kilometer (RKM) 266 (River Mile (RM) 165) near the confluence with the Grande Ronde River. In general, the methods for all studies integrated pre-dam river data and hydraulic modeling into a geographic information system (GIS). The water discharge data used for all modeling and analysis was derived from United States Geological Survey (USGS) gage data and adjusted streamflow and storage data from the Bonneville Power Administration (BPA, 1993).

Pre-dam channel characteristics were evaluated by classifying the lower Snake River into distinct geomorphic units at two different scales: watershed and reach. The watershed-scale classification was based on geology and physiography, as well as channel planform data from pre-dam maps (ca.

1934). Reach scale classification and characterization (e.g., stream power, pool/riffle/run) was based on the analysis of hydraulic geometry and channel morphology at sampled cross sections. Hydraulics at each cross section were simulated using one-dimensional (MASS1) and two-dimensional (MASS2) unsteady flow models.

Potential fall chinook spawning and rearing habitat was identified and then quantified by two separate methods: 1) a geomorphic spawning habitat model for fall chinook was developed by integrating historic, pre-dam spawning data (e.g., location, redd density) with geomorphic characteristics, and 2) spawning and rearing habitat criteria was applied to the hydrodynamic conditions simulated by flow models.

Estimates of flows required to mobilize sediments after drawdown were also estimated by two methods: 1) using simulated depth-averaged velocities from MASS2, in combination with sediment movement criteria based on critical velocity or shear stress, and, 2) using the geomorphic competency method which uses a threshold of 1.0-year flood based on the annual maximum series.

Conclusions

Our analysis indicated that, prior to impoundment, the lower Snake River exhibited heterogeneous characteristics ranging from those typical of alluvial reaches to those typical of bedrock-confined reaches in large rivers. In general, the pre-dam channel was a morphologically diverse, coarse-bedded, stable river, possessing a meandering thalweg and classic pool-riffle longitudinal bedform profile.

The geomorphic model of fall chinook spawning habitat and the application of habitat criteria to MASS2 estimates differed somewhat in the location and amount of spawning habitat that would be available with the natural river alternative. The geomorphic model identified 54.9 percent of the lower Snake River reach as potential spawning habitat while the application of habitat criteria predicted 23.5 percent.

Analysis of historic and contemporary discharge records indicates that regulated flow regimes under dam breaching will be competent enough to maintain channel characteristics and riverine processes (e.g., channelbed mobilization). The time required before the realization of these characteristics and processes depends on many interrelated factors, including an initial 5-year to 10-year period of erosion and transport of fine sediments accumulated in the reservoirs since dam construction. After the bulk of those fine sediments are removed, the competency of the regulated flow regime (particularly the annual maximum discharge) will be sufficient to mobilize the channelbed surface.

Flows required for mobilization of coarse sediment under the dam breaching alternative were estimated at 95,600 cfs using the geomorphic competency method and a threshold of 1.0-year flood and at 111,500 cfs using the MASS2 predicted velocities and shear stress criteria multiplied by 1.5 to allow for added energy required to initiate motion in a resting particle.

The time required for the initiation of such processes depends on the annual flow regimes during the period following drawdown, particularly the frequency and duration of annual maximum discharge equaling or exceeding the pre-major storage period.

Part 1

Assessment of Restoring Pre-dam Channel Morphology, Salmonid Habitats, and Riverine Processes through Drawdown: Snake River

1. Introduction

1.1 Objectives

The research described herein set out to address the question. "To what extent can mainstem habitats and riverine processes required for salmon production be achieved by near-dam breaching?" We focused on three objectives for this study. The first objective was to describe the physical characteristics and habitats of the pre-dam river. Characterizing and quantifying the pre-dam channel morphology provides a starting point for determining future channel characteristics and habitats because it establishes the difference between known pre-dam channel morphology and present day conditions. The second objective was to quantify the geomorphic features that describe salmon production areas. The third objective was to evaluate changes in the flow regime under near-dam breaching—perhaps the most important controlling factor of channel morphology and riverine processes. This objective is particularly important because the river will continue to be influenced by regulated flows from the operation of upstream storage reservoirs and hydropower facilities located on the mainstem Snake River and tributaries (e.g., the Hells Canyon Dam complex in the middle Snake River and Dworshak Dam on the North Fork of the Clearwater River). The regulated flow regimes must be competent enough to erode and transport fine sediments accumulated in the reservoirs since dam construction, and also to maintain other geomorphic processes (e.g., channelbed mobilization).

1.2 Background

Snake River populations of salmon and steelhead have declined during the past 30+ years, leading to their protection under the U. S. Endangered Species Act (ESA). In 1991, Snake River sockeye salmon (*Oncorhynchus nerka*) were listed under the ESA as endangered. In 1992, Snake River spring/summer and fall chinook salmon (*O. tshawytscha*) were listed as threatened. In 1998, Snake River steelhead (*O. mykiss*) were listed as threatened. These listings prompted the National Marine Fisheries Service (NMFS) to call for an evaluation of structural and operational modifications to the four hydroelectric dams operated by the U. S. Army Corps of Engineers (Corps) on the lower Snake River (NMFS, 1995; NMFS, 1998).

There is a nearly continuous reservoir system on the lower Snake River since the construction of the four lower Snake River dams (1961 to 1975). The only areas currently exhibiting riverine characteristics are the tailraces downriver of each dam. The lack of riverine habitat has impacted the life history strategies (e.g., juvenile migration from tributary to ocean) for all populations of Snake River salmonids.

Early modifications to dam operations were focused on reducing travel time through the reservoirs for the juveniles during their spring migration. One method used for increasing water velocity, and thereby reducing travel times, was to increase the spill volume through the dams (also known as drawdown).

Recent work indicates that alluvial reaches of large rivers are particularly important to the spawning success of fall chinook salmon (Geist and Dauble, 1998; Dauble and Geist, In Press). Alluvial rivers are those that are capable of shaping their own bed and bank—they are self-formed (Richards, 1982). Their channel morphology results from the entrainment, transportation, and deposition of

unconsolidated sediments throughout the channel course (Richards, 1982). This morphology is maintained in "dynamic quasi-equilibrium"—where sediment is transported through or stored within the channel (dynamic), but the channel morphology remains relatively stable over time (quasi-equilibrium) even though the channel may not be static (Richards, 1982; Knighton, 1984). In ideal alluvial rivers, this morphological relationship is maintained when the rates of sediment supply and sediment transport are roughly equal (Hey, 1997). Natural alluvial channels are morphologically diverse. They exhibit a classic pool-riffle longitudinal profile where deeper pool sections alternate with the shallower inflection areas of riffles (Hey, 1997). Historical accounts of salmonid spawning in the lower Snake River (Fulton, 1968; Fulton, 1970) suggest that some segments exhibited alluvial characteristics prior to dam construction.

The rehabilitation and enhancement of pre-dam biotic and abiotic components in the lower Snake River depends on the extent to which pre-dam morphological characteristics can be restored—particularly alluvial and partially-alluvial reaches. This approach assumes that those characteristics supported healthy salmonid populations in the past and have the capacity to do so in the future.

2. Study Area

The area studied for this appendix extends from the mouth of the Snake River (at its confluence with the Columbia River) to 165 miles upriver near the confluence with the Grande Ronde River (Figure 2-1). The lower Snake River watershed drains approximately 104,000 square miles (mi^2) of Idaho and Washington. Mean annual discharge at the uppermost dam in the area studied (Lower Granite Dam) is 49,800 cubic feet per second (cfs), while mean annual peak discharge is approximately 177,000 cfs. The study area lies within a climatic area that receives average annual precipitation of 16 inches, with average maximum winter temperatures of 40° Fahrenheit (F) and average August temperatures of 64° F. The dominant potential vegetation types are warm-dry shrublands, warm-dry herbaceous lands, and cool-moist shrublands (Quigley and Arbelbide, 1997).

Elevations in the study area range from 340 to 3000 feet above mean sea level, and include areas of broad valleys with gentle slopes, as well as areas of deep, confined canyons with steep walls. The lower Snake River valley has a complex geologic history. Basalt bedrock, originating during periods of volcanism between 17 and 6 million years ago represents much of the current river valley (Schuster et al., 1997), forming steep, bedrock-exposed valley walls known as the Snake River breaks. About 14,500 years ago, Pleistocene Lake Bonneville (in present-day northern Utah) spilled over and flooded into the Snake River valley, depositing significant amounts of alluvium with clast diameter ranging in size from less than 10 centimeters to more than 10 meters (O'Connor, 1993). The flood followed the course of the present-day Snake and Columbia rivers before entering the Pacific Ocean (O'Connor 1993). Subsequent flood events (as many as 100) from glacial Lake Missoula, between 14,500 and 12,000 years ago, deposited immense amounts of gravel, sand, and silt over the Bonneville flood deposits in the lower end of the study area (Baker and Bunker, 1985; O'Connor, 1993).

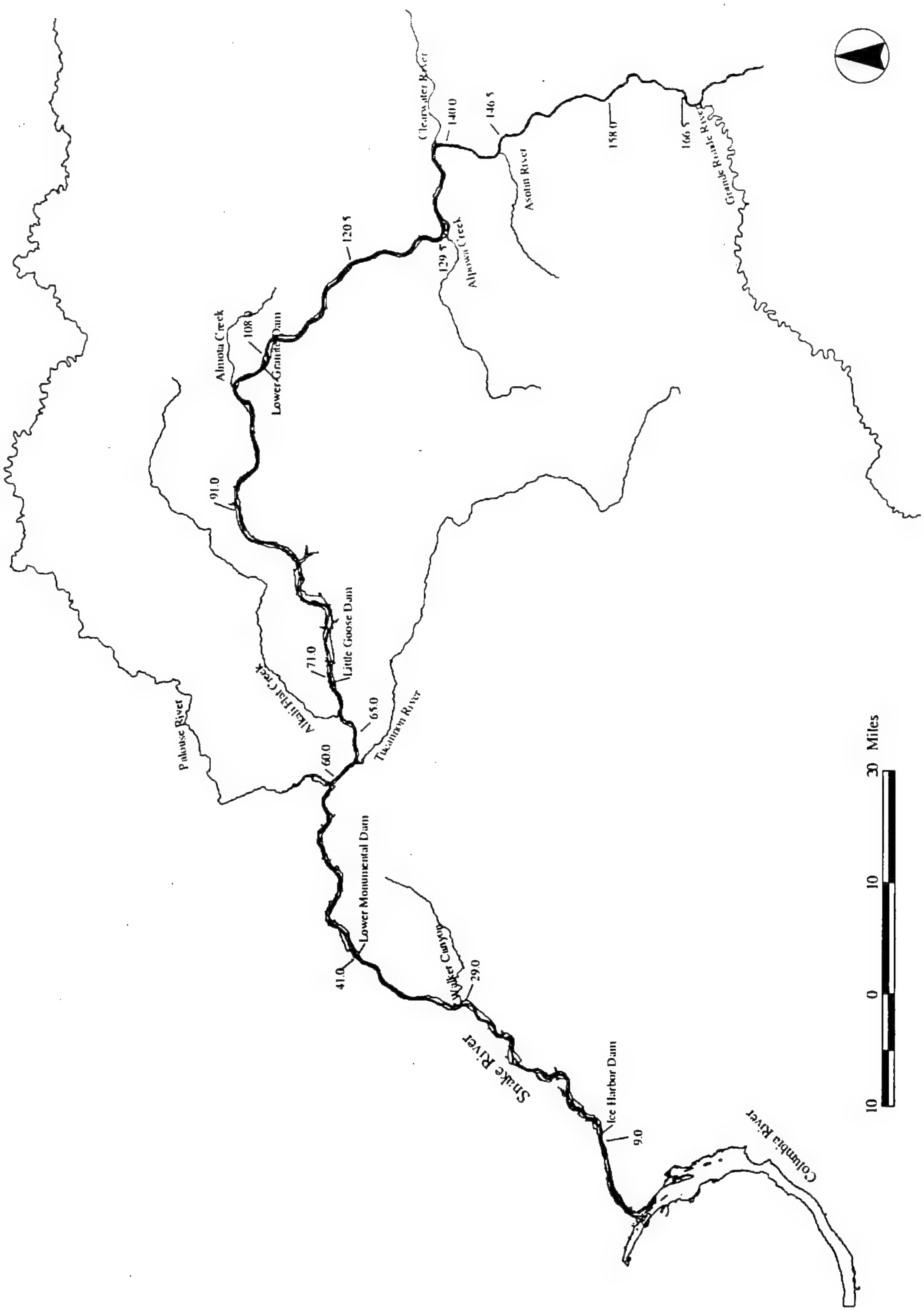

Figure 2-1. Analysis Area

3. Methods

Classification and characterization schemes of rivers based on morphology, process, and habitats are plentiful. The methods of interest for this analysis are those relating to descriptive morphology and indicators of river processes. The classification of river segments into unique groups is an endeavor dating back to the 19th century. Davis (1899) grouped rivers by their position in youthful, mature, and old landscapes. Leopold and Wolman (1957) investigated the range of channel patterns in planform; and arrived at groupings according to braided, meandering, and straight. Schumm (1963) provided an initial classification scheme based on sediment transport regime, which he later modified to include channel pattern and relative stability (Schumm, 1977). Kellerhals et al. (1976) proposed a classification system based on an extensive collection of river reach survey data for rivers in Alberta, Canada (Kellerhals et al., 1972). Their system incorporates channel patterns, the presence and type of depositional features, and consideration of valley features (i.e., confinement and geology). This was later modified by Church and Rood (1983) in an effort to compile many published river study data sets into a catalogue for the study of alluvial river channel regime. Montgomery and Buffington (1993) also incorporated coarse and fine scale parameters in their classification framework. They proposed a landscape and channel classification system for assessing watershed response to environmental change. In their system, channel reaches are classified as source, transport, or response relative to the initiation of change within the watershed. Any comprehensive assessment of channel morphology and processes should consider the influence of the valley on the river; as well as the planform, cross-sectional, and longitudinal dimensions of river reaches (Thorne, 1997). Rosgen's 1994 classification system fits this description, and has been described as possibly the most comprehensive system for classification yet devised (Hey, 1997). The characterization and classification system implemented in this study is a combination and modification of Kellerhals et al. (1976) and Rosgen (1996).

The methods described below address each of the three study objectives: 1) describe the physical characteristics and habitats of the pre-dam river; 2) quantify the geomorphic features that describe salmon production areas; and 3) evaluate changes in the flow regime under dam breaching.

3.1 Coarse Scale Geomorphic Characterization

Characterization of the lower Snake River began with an evaluation of the watershed-scale controlling factors of channel morphology (e.g., geology, physiography, longitudinal profile, and discharge). This scale was the initial level of assessment in an attempt to classify the 266 km (165-mile) study area into distinct geomorphic units. The objectives were to minimize the variability within each unit, maximize the variability between units, and classify the units based on parameters that would provide indicators of channel-forming processes, channel morphology at the reach scale, and reach scale response potential to change.

The coarse scale (level 1) classification was based on geology, physiography, and channel planform. Data for geologic features of the area were incorporated into a GIS. The data originated at a scale of 1:500,000 and contained descriptions of geologic formation, rock type, age, and major lithology (Johnson and Raines, 1996; Raines and Johnson, 1996). The lower Snake River valley was subsequently classified into three classes based on geological formations (unconsolidated sediments, bedrock, and mixed/unconsolidated bedrock), and compared with a 1:250,000 scale hard copy map

of geologic features in the analysis area (Schuster et al., 1997). The geologic features within 1.6 km (1 mile) of the river channel were used in the level 1 classification.

The assessment of physiography involved the evaluation of the river valley morphology as a whole. It involved an interpretation of structural controls and lithology, landforms, and fluvial processes. Primary attention was given to the relationship between the river channel and the valley walls, providing an indication of the lateral and vertical control the valley imposes on the river. Interpretation of these features and processes were based on models of landform that were incorporated into the GIS. Individual digital elevation models (DEMs), with a 30 meter cell resolution and a scale of 1:24,000, were combined into one DEM for the entire analysis area. The resulting DEM was subjected to a hillshading algorithm, which allows for easy visual distinction of topographical relief. A similar hillshaded DEM model was built for the river channel (bathymetry) and near-shore topography for the entire analysis area. That DEM was based on depth soundings taken during low flow periods in 1933 and 1934, which were mapped at 1:2,000 for the entire analysis area by the Corps. Near-shore topography up to several hundred feet in elevation was also mapped at 1:2,000. These data were incorporated into the GIS and transformed into a three-dimensional surface for producing the hillshaded DEM. The resulting DEMs were interpreted for the presence of different valley types (i.e., broad, gently-sloping valley walls vs. deep, confined, steep-sloped valley walls), structural containment by the valley walls, and fluvial processes (e.g., scour and fill) within the river channel. The physiographic interpretation resulted in two classes being used for the level 1 classification: confined and moderately confined. These two classes describe the degree of structural confinement of the channel within the valley walls. Confinement was generally indicated where the channel occupied the majority of the valley bottom, with little alternate bar (channel side bar) development.

Channel planform was the final parameter used in the level 1 classification. The 1:2,000 scale pre-dam Corps maps discussed earlier were incorporated into the GIS. The maps depict shoreline, islands, and bars at low flow. The level 1 classification included channel pattern (e.g., sinuosity) and depositional features (i.e., islands and bars). River sinuosity (P) is used to indicate how the river has adjusted its slope relative to the slope of its valley. For a given river segment, P was calculated as the ratio of river channel length to valley length (Richards, 1982).

Planform depositional features were incorporated into the level 1 classification by delineating river segments into two classes: islands or bars present, and islands or bars absent. Only genetic features (those constructed by the present-day river through the course of lateral shifting or flooding (Kellerhals et al., 1976; Kellerhals and Church, 1989)) were included in the classification. The term, "genetic features," is used differentiate them from terraces deposited during cataclysmic events (e.g., the Bonneville Flood) that were constructed at elevations exceeding present-day peak flood stages. Genetic features were interpreted from the pre-dam maps and hillshaded DEMs, based on their elevation relative to the water surface elevation.

The level 1 classification was completed by using GIS map overlay techniques based on data layers depicting geology, physiography, and channel planform. The data layers were combined to find the spatial relationship among the three characteristics.

3.2 Reach Scale Classification (Level 2)

Characterization of the lower Snake River at the reach scale was based on an analysis of hydraulic geometry and channel morphology at sampled cross sections. Hydraulics at each cross section were

simulated, using both one-dimensional (MASS1) and two-dimensional (MASS2) unsteady flow models developed at the Pacific Northwest National Laboratory (Richmond and Perkins, 1999). The MASS1 model was used to estimate cross-section averages of hydraulic parameters, while the MASS2 model was used to estimate depth-averaged hydraulic parameters in a horizontal plane (e.g., lateral variation in velocity). The physical basis for the cross sections was the pre-dam channel morphology data (i.e., bathymetry surface and planform characteristics) incorporated into the GIS from the 1934 Corps maps. A total of 338 cross sections, spaced 0.4 to 0.8 km (0.25 to 0.5 mile) apart, were placed in the 266-km (165-mile) study area for the MASS1 modeling. The MASS2 modeling results were extracted at cross sections spaced 0.16 km (0.1 mile) apart in order to identify fine-scale lateral and longitudinal variations in the hydraulic parameters. The models were run for flow scenarios approximating the 10-, 50-, and 90 percent exceedance discharges (Q10 = 3,157 cms (111,500 cfs), Q50 = 898 cms (31,710 cfs), Q90 = 472 cms (16,680 cfs), respectively) based on 67 years of mean monthly flow at Lower Granite Dam. At each cross section, MASS1 model outputs included average estimates of discharge, water surface elevation, velocity, thalweg elevation, cross-sectional area, and hydraulic radius. Three additional characteristics for each cross section were computed from these estimates: width to depth ratio (F), water surface slope (S), and entrenchment ratio (ER). The level 2 classification used F and S values based on the Q50 hydraulic results. The ER characteristic for the level 2 classification was based on the ratio of the top width for the Q10 flow (i.e., high flow) to the top width for the Q50 flow. The ER characteristic is used as an index of channel shape and entrenchment, where values approaching 1 indicate an entrenched channel capable of containing a high flow within its banks (Rosgen, 1996).

Channel substrate data were also incorporated into the level 2 classification. The 1934 Corps maps contained handwritten notations of substrate types for the river channel and shoreline. The notes are qualitative assessments of substrate type, and provide only a general idea of grain sizes and spatial distribution. Limitations encountered with these data include: 1) there are no spatial demarcations on the maps indicating spatial extent of substrate types; 2) different words are used to describe the same size classes (e.g., "gravel to 6 in" and "rocks to 6 in"); 3) substrate descriptions are often combined with no indication of dominance or relative abundance (e.g., "sand and gravel 1 to 8 inches"); and 4) substrate descriptions often describe more than one substrate class relative to the American Geophysical Union (AGU) grain size classification (Vanoni, 1975). For example, "gravel to 6 inches" would include all classes between very fine gravel (2 millimeters, .08 inches) and large cobble (152.4 millimeters, 6 inches). The handwritten notations of substrate type were incorporated into the GIS as point samples. The notes for each point sample were converted into one of five classes according to the appropriate AGU grain size classification (Table 3-1). Where the notes of grain sizes ranged over more than one AGU grain size classification, the median of that range was applied to that point. The sampling points were color coded according to the grain size class and plotted with the GIS. Areas of the river channel were subsequently interpreted as to the dominant and subdominant grain size class, and segments of the river were delineated accordingly. The qualitative nature of the substrate data led to a further reclassification by grouping grain size classes. For example, all sampling points in the cobble and gravel classes were grouped into one class without indication of dominance and subdominance (Table 3-2). A resulting substrate class was then assigned to each cross section.

The level 2 classification proceeded by assigning a value for each characteristic (D, F, S, ER) to each cross section. The definitions and categories for each characteristic are provided in Table 3-2.

Table 3-1. Grain Size Classification

Size Class	Grain Diameter (millimeters)
Bedrock	
Boulder	>256
Cobble	64-256
Gravel	2-64
Sand	0.0625 – 2

Table 3-2. Level 2 Characteristics

Level 2 Characteristic	Definition	Code
Substrate (*D*)	Bedrock/boulder	*D*1
	Cobble/gravel	*D*34
	Sand	*D*5
Width: Depth ratio (F)	Low to moderate, <20	*F-*
	Moderate to high, >=20	*F+*
Water surface slope (S)	Low to moderate, <0.001	*S-*
50 percent exceedance flow	Moderate to high, >=0.001	*S+*
Entrenchment ratio (*ER*)	Entrenched, <1.4	*ER-*
Width of 10 percent to width of 50 percent exceedance flow	Moderate, >=1.4	*ER+*

Table 3-3. Example and Description of Level 2 Classification

Level 2 Class			*F_bi* D34 F+ S- ER-		
Characteristic:	F_bi	*D34*	*F+*	*S-*	*ER-*
Description:	See level 1 code	Dominated by cobble/gravel substrate	Moderately high width-to-depth ratio	Low-to-moderate water surface slope	Entrenched within the valley bottom

The level 2 class of a given cross section was determined by combining its level 1 class with its D, F, S, and ER values (see Table 3-3 for an example).

3.3 Additional Hydraulic and Geomorphic Characteristics

Hydraulic parameters and indices of channel shape were also summarized for each cross section. The Q_{50} flow was used to calculate mean depth, width, and velocity, width to depth ratio (*F*), maximum depth to mean depth ratio (d_{max}/d), and unit stream power (•). Stream power per unit bed area was calculated as:

$$\omega = pgdvs_e$$

where ω is the fluid density, g is gravitational acceleration, d is depth, v is velocity, and s_e is the energy slope approximated by the water surface slope.

Additional spatial assessment of pool, run, and riffle/rapid habitat features was completed based on hydraulic modeling results. Typical parameters used include combinations of velocity/depth ratio, Froude number, and water surface slope. These parameters are typically calibrated to visual

assessments of pool, run, and riffle habitat types made during field visits. Once calibrated, the parameters are used to predict the quantity and spatial composition of the habitat features (Jowett, 1993). The physical criteria used to delineate habitat features (e.g., velocity/depth ratio <1.24 indicates pool habitat) are specific to the river for which the criteria were developed, and are generally not transferable to different rivers. This required us to correlate visual estimates of pool, riffle, run habitat from pre-dam maps with hydraulic parameters estimated through modeling. The spatial assessment of pool, run, and riffle/rapid habitats for the lower Snake River was based on the calculated velocity/depth ratio for the Q_{50} flow. The linear (upstream/downstream) extent of some rapids were depicted on the 1934 pre-dam maps and were digitized into a GIS data layer. Pool, riffle, or other similar habitat types were not depicted on the 1934 pre-dam maps, and therefore could not be used for correlating hydraulic estimates. The extent of pre-dam rapids was plotted on the GIS on top of the data layer depicting velocity/depth ratio. This map overlay was used to determine the velocity/depth criteria distinguishing rapids from other habitats. Criteria distinguishing pool and run habitats were estimated based on an interpretation of the remaining velocity/depth ratios and channel morphology. The habitat criteria are based on the following velocity/depth ratios: pool 0.0—0.50, run 0.51—1.20, riffle/rapid >1.20.

3.4 Geomorphic Features and Salmon Production Areas

Prior to hydroelectric development in the lower Snake River, no comprehensive surveys of any general spawning area for fall chinook or steelhead were ever conducted, as far as the author knows. During the hydroelectric development period (beginning in the 1950s), spawning surveys were initiated to provide baseline information on the distribution and numbers of salmon redds present prior to construction of planned hydro projects (Battelle and USGS, 1999). The locations of pre-dam spawning areas in the lower Snake River were compiled from Fulton (1968) and Battelle and USGS (1999). These data sets provide the best quantitative measure of habitat used, however, it is unknown whether these same habitats were used by salmonids to the same extent before Europeans settled in the Pacific Northwest.

All quantitative data sets for fall chinook spawning locations were incorporated into the GIS through the use of dynamic segmentation. These data sets were built as linear event tables containing locational information (e.g., from river km, to river km), attribute data, and database keys linking to the reference source for the attribute data. The event tables were then linked to their location in the lower Snake River through the use of 1:100,000 scale Pacific Northwest River Reach Files (PNW RRF) obtained from the USGS and StreamNet. These files include GIS data layers containing line segments that represent the channel midline.

We used the geology and planform data layers to quantify the geologic composition and availability of depositional features along the lower Snake River. The 1:100,000 scale PNW RRF were segmented into 500 m (1640 ft) linear sections and used as the base layer for delineating geologic and depositional features. The delineation of these features correlated spatially with the delineation of fall chinook spawning locations described earlier.

The geologic composition of the right and left bank (facing downriver) for each 500 m (1640 ft) segment was estimated through the use of nearest neighbor analysis in the GIS. Each 500 m (1640 ft) segment was assigned the geologic attributes (geologic formation, rock type, age, major lithology, and bedrock/unconsolidated classification) of the nearest right-bank and left-bank geologic unit. A composite geologic typing of each 500 m (1640 ft) segment was calculated by

averaging the right-bank and left bank bedrock/unconsolidated classification. Thus, each 500 m (1640 ft) segment could be one of three types: 100 percent unconsolidated, 50/50 unconsolidated /bedrock, 100 percent bedrock. The same composite geologic typing was completed for longer contiguous river sections as well (e.g., 32 km [20 mi]) spawning section), resulting in different percentages of geologic composition for these sections as a whole. Planform depositional features (bars and islands) were interpreted from planform GIS data layers. The data layers used included those depicting right- and left-bank shorelines, cutoff channels, islands, and near-shore topography (contour lines and hillshaded DEMs). Depositional features were incorporated into the analysis by delineating each 500 m (1640 ft) segment into one of three classes: islands or bars present, islands or bars absent, and unknown. Only genetic features were included in the classification. A composite depositional typing for contiguous river sections (e.g., 32 km [20 mi] spawning section) was calculated by determining the proportion of a given contiguous section classified as depositional features present, absent, and unknown.

Redd density data for fall chinook spawning in the Columbia and Snake rivers was used to evaluate the relationship between the geomorphic features described above and spawning areas (Battelle and USGS, 1999). These geomorphic features have previously been shown to be important for describing fall chinook spawning areas (Dauble and Geist, in press). Based on the relationship between redd densities and geomorphic features we created a geomorphic spawning habitat model where segments of river were considered usable if they contained greater than 50 percent unconsolidated sediment, contained bars and/or islands, and were less than 0.0005 in longitudinal gradient. River segments that met these criteria were considered suitable fall chinook salmon production areas while those that failed to meet all the criteria were considered unsuitable spawning habitat.

3.5 Flow Regime and Sediment Transport

Flow records analyzed for this study represent discharge of the Snake River near the upriver end of the study area and downriver of the confluence with the Clearwater River. Daily discharge records for the period January 1, 1929 through December 31, 1973 were obtained from the USGS gage (13343500) near Clarkston, Washington. This gage was discontinued after December 31, 1973. To estimate daily discharge at the same location after this period, we summed the discharges from three different gages approximating the total aggregate flow to that location. Daily discharge records for the period January 1, 1974 through June 30, 1996 were obtained from the USGS gages on the Snake River near Anatone (13334300), on Asotin Creek near Asotin, Washington (13334700), and on the Clearwater River at Spaulding, Washington (13342500). The discharge record for Asotin Creek ends at June 30, 1996, but was extended through linear regression with the USGS gage on the Grande Ronde River (13333000) to be coincident with the time steps of the other gages. Total discharge for the period July 1, 1996 through September 30, 1998 was estimated by summing the daily records from the Anatone gage, the extended Asotin Creek records, and the Spaulding gage.

The flow regime for the time period prior to major hydroelectric development (pre-major storage, 1929-1958) was assumed to be indicative of the flow regimes that shaped and maintained the river during that period. The flow regime after major hydroelectric development (post-major storage, 1959-1998) was assumed to be indicative of the flow regimes that will persist into the future, even after modification of the four lower Snake River dams. The constructed flow record represents discharge upriver of the four lower Snake River dams and downriver from the hydroelectric dams and storage reservoirs that will be unaffected by modifications to the lower Snake River dams.

The limited availability of present substrate conditions in the entire lower Snake River inhibits the estimation of sediment transport following dam breaching. The most data available is for that area upriver of Lower Granite Dam. Estimates of the time required to remove sediment accumulated in Lower Granite reservoir were based on estimates of available sediment and one-dimensional hydrodynamic modeling simulations (see Hanrahan et al., 1998, for details).

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4. Results and Discussion

4.1 Coarse Scale Geomorphic Characterization (Level 1)

When viewed in planform the lower Snake River exhibits a meandering course, but geomorphologically it is a straight or slightly sinuous river (P <1.2). The river possesses the characteristics of passive meandering, where the planform pattern is imposed by the local landform (Richards, 1982; Thorne, 1997). This characteristic is distinct from completely self-formed alluvial channels that are actively and freely forming the valley bottom (active meandering). Because of the homogeneity of low P values throughout the study area, sinuosity was not a primary determining factor in the coarse scale classification.

The lower Snake River was delineated into three classes, which are described in Table 4-1. The analysis area contains 14 percent of the C_{bi} class, 26 percent of the F class, and 60 percent of the F_{bi} class (Figures 4-1 through 4-3). Most alluvial or partially-alluvial reaches of the lower Snake River fall under the level-1 classifications of C_{bi} and F_{bi}. Bedrock-confined and colluvial reaches are found mostly in the areas of level-1 F classifications. Two general areas within the lower Snake River are classified as C_{bi}: from the mouth upriver to approximately RM 16.0, and near the confluence with the Clearwater River, from RM 134 to 142. For comparison sake, the Hanford Reach of the Columbia River is also classified as C_{bi} when using the same classification methods used in this study. Areas classified as F_{bi} are sporadic, with one large contiguous section extending from approximately RM 66 to 120. The distribution of areas classified as F is similarly patchy, although one large section extends from approximately RM 44 to 66. Within each level-1 class, a diversity of channel forms was classified at the cross section scale (level 2).

Table 4-1. Level 1 Classification

Level 1 Code	Description
C_bi	The major lithology is dominated by unconsolidated sedimentary rocks and deposits. The river channel is moderately confined by the valley/canyon walls; indicating it is neither totally confined nor totally unconfined. Bars and/or islands are present.
F_bi	The major lithology is a mix of unconsolidated sedimentary rocks/deposits and basalt bedrock. The river channel is moderately confined by the valley/canyon walls; indicating it is neither totally confined nor totally unconfined. Bars and/or islands are present.
F	The major lithology is a mix of unconsolidated sedimentary rocks/deposits and basalt bedrock. The river channel is highly confined by the valley/canyon walls, and occupies almost the entire valley bottom. Bars and/or islands are absent.

4.2 Reach Scale Classification (Level 2)

Although geomorphologically straight rivers such as the lower Snake River do not follow an actively sinuous path, many do possess a regularly meandering thalweg and filament of maximum velocity (Richards, 1982; Thorne, 1997). Results from the 2-dimensional hydrodynamic modeling (MASS2) indicate a meandering thalweg (Figure 4-4) and filament of maximum velocity (Figure 4-5). These characteristics are closely related to vertical oscillations in bedforms (pool/riffle), which are in turn a dynamic response to non-uniform velocity, boundary shear stress, and sediment transport (Thorne, 1997). These reach level characteristics were further evaluated through the analysis of hydraulic geometry and longitudinal profiles in the reach scale classification.

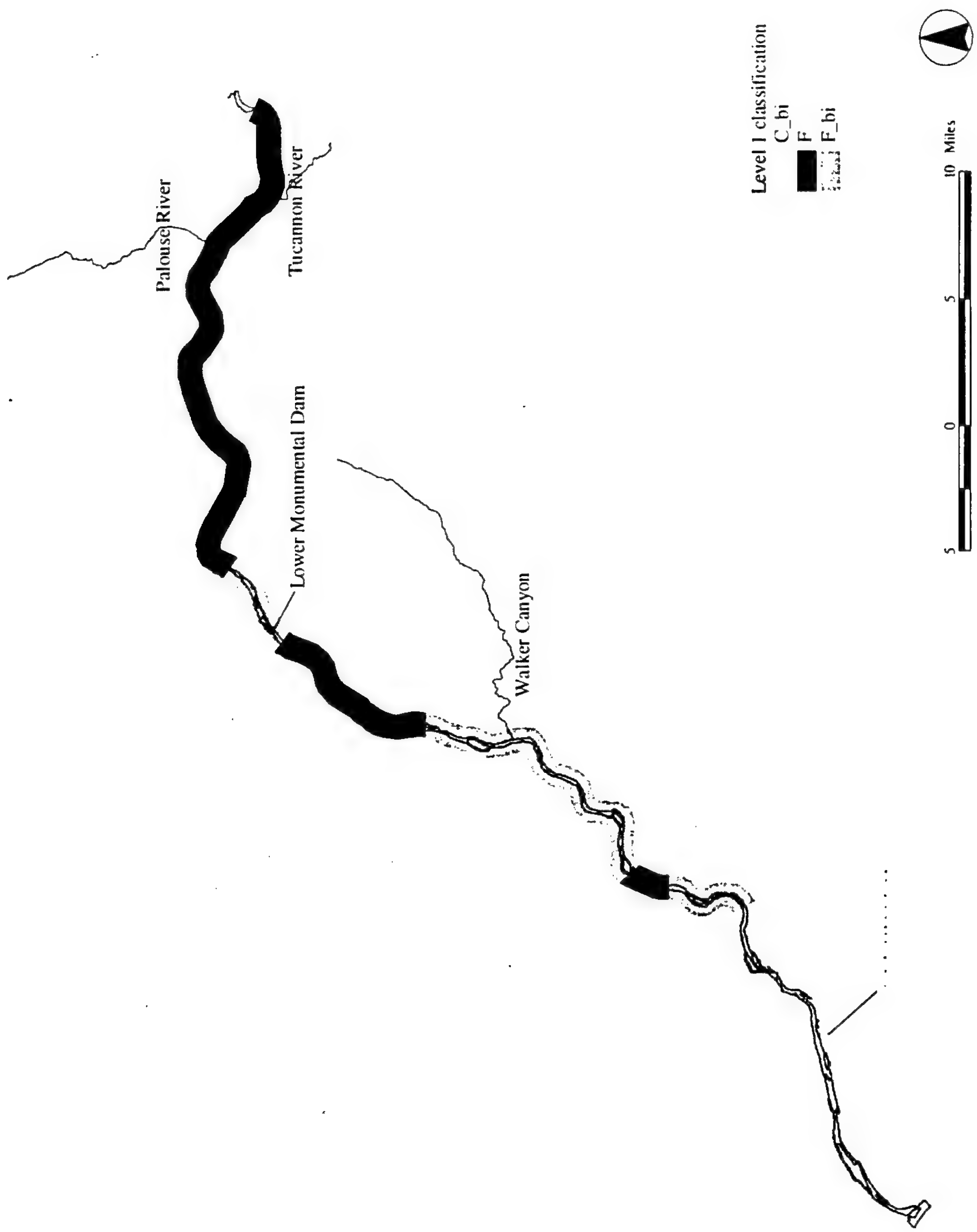


Figure 4-1. Level 1 Classification, Ice Harbor to Tucannon River

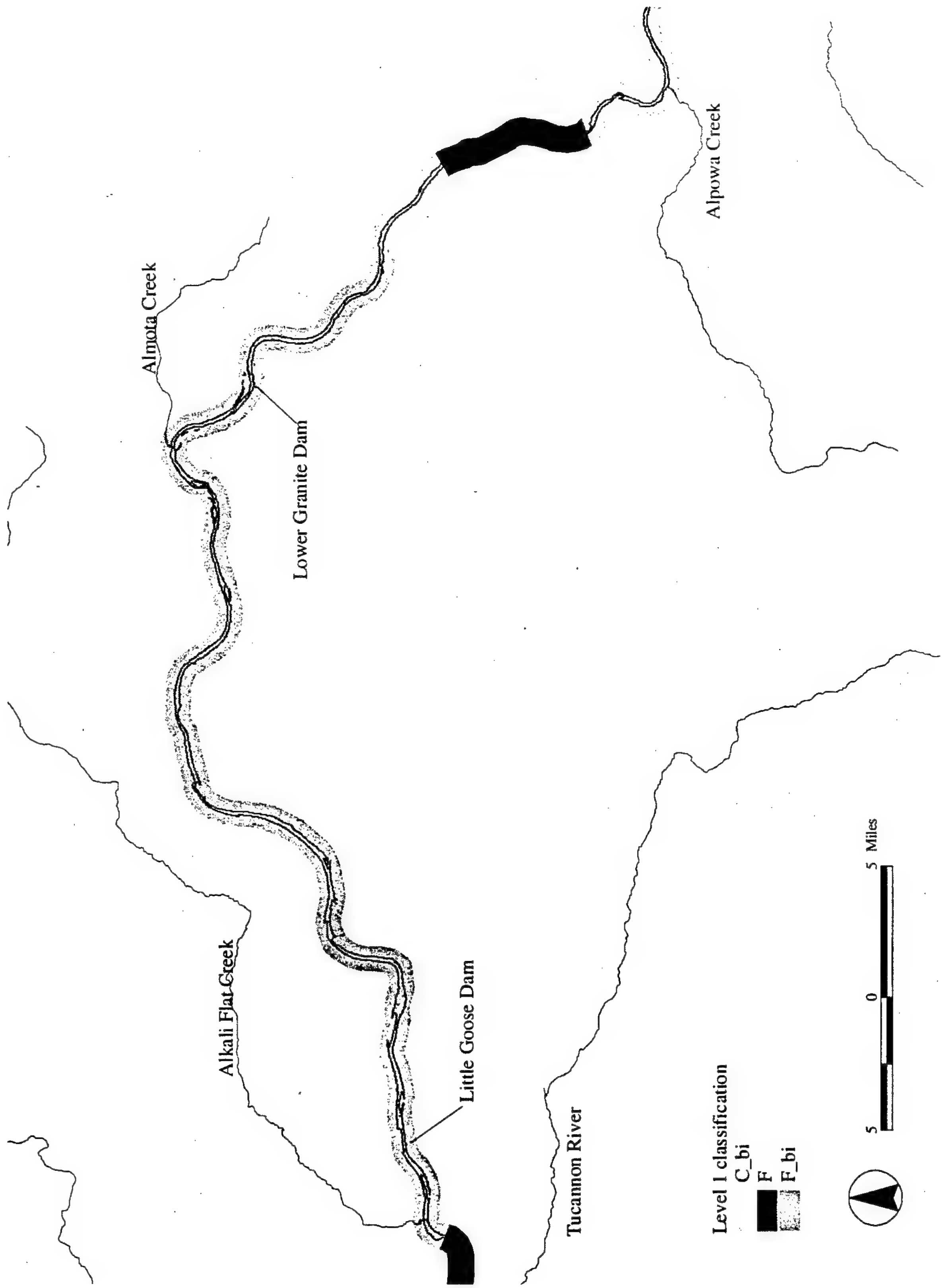


Figure 4-2. Level 1 Classification, Tucannon River to Alpowa Creek

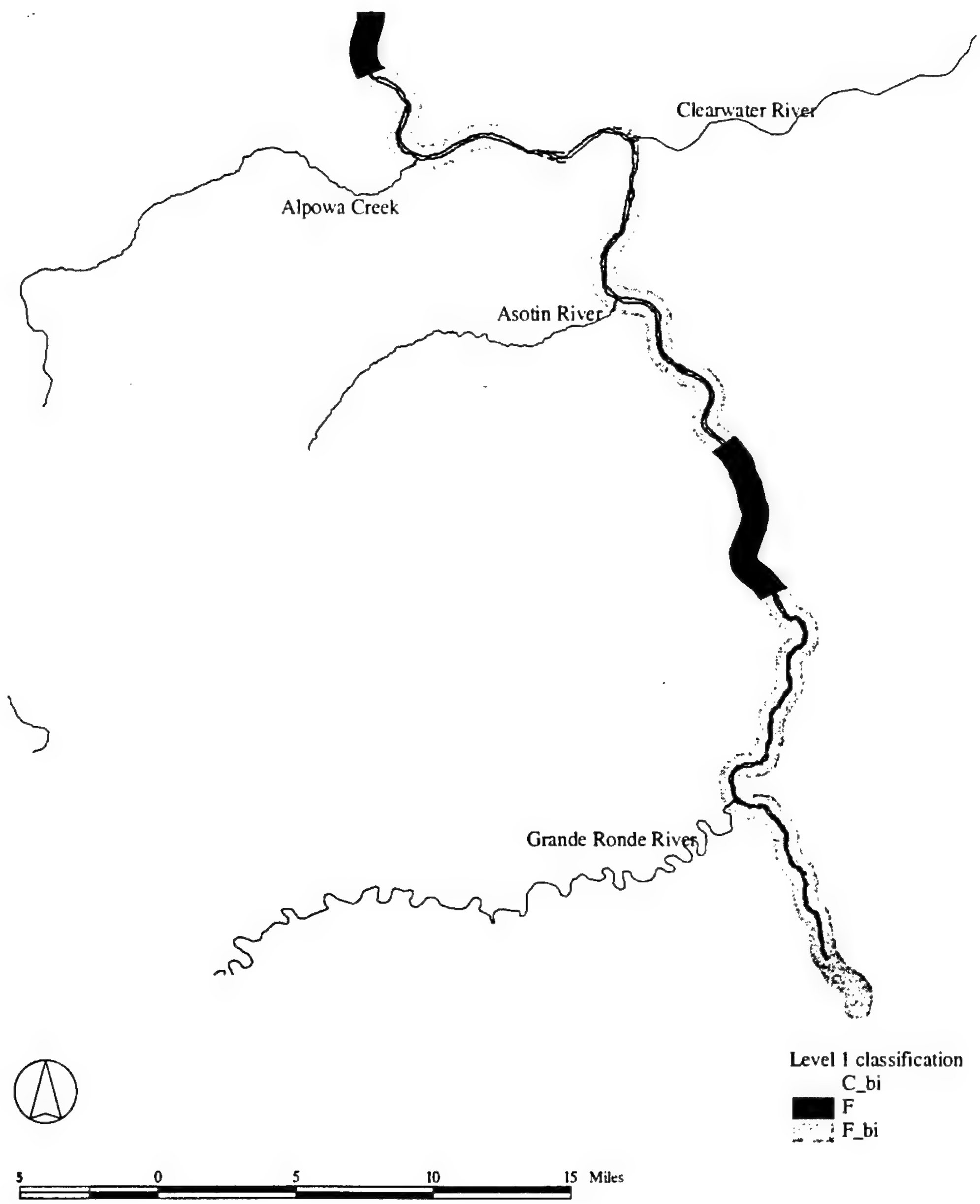


Figure 4-3. Level 1 Classification, Alpowa Creek to Grande Ronde River

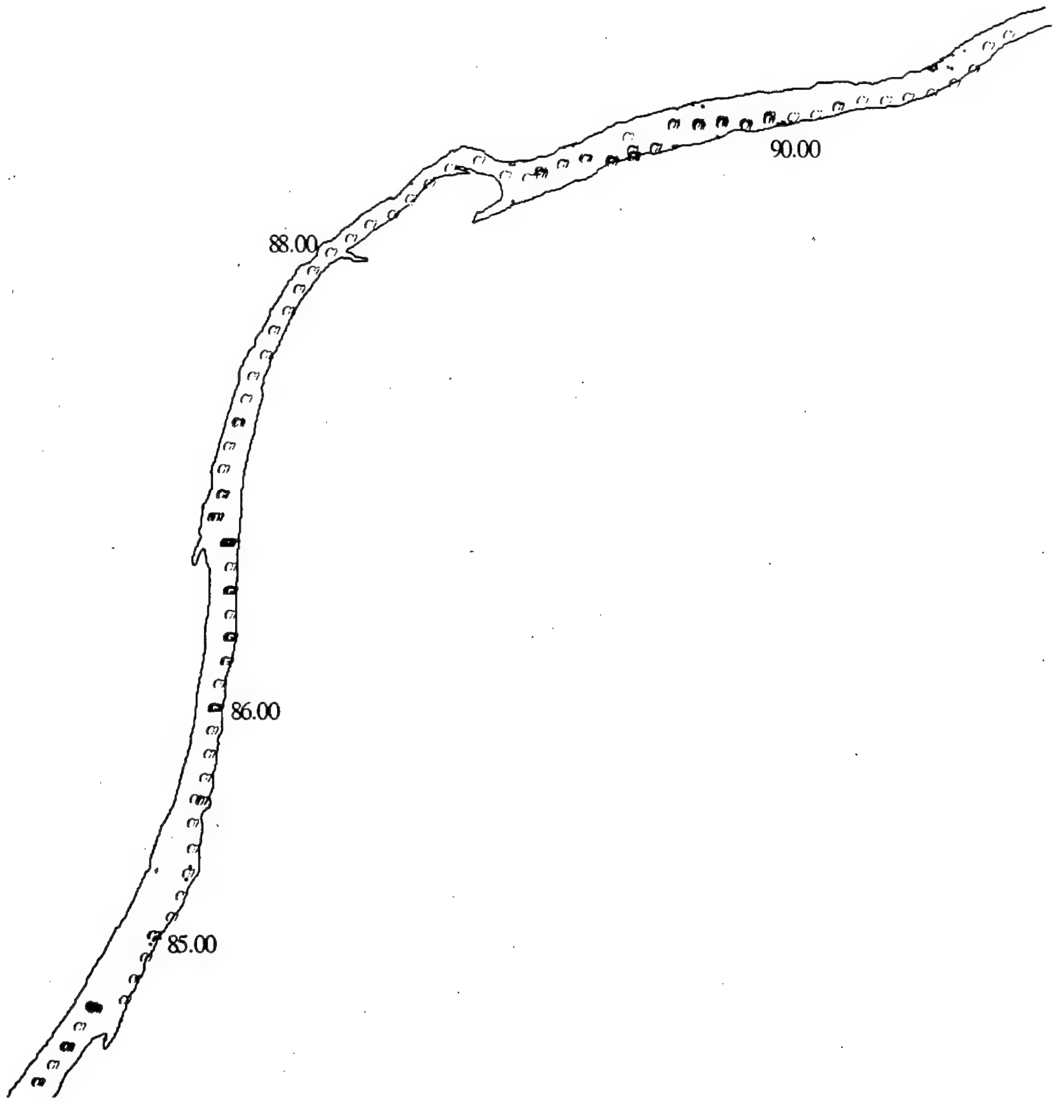


Figure 4-4. Example of Meandering Thalweg

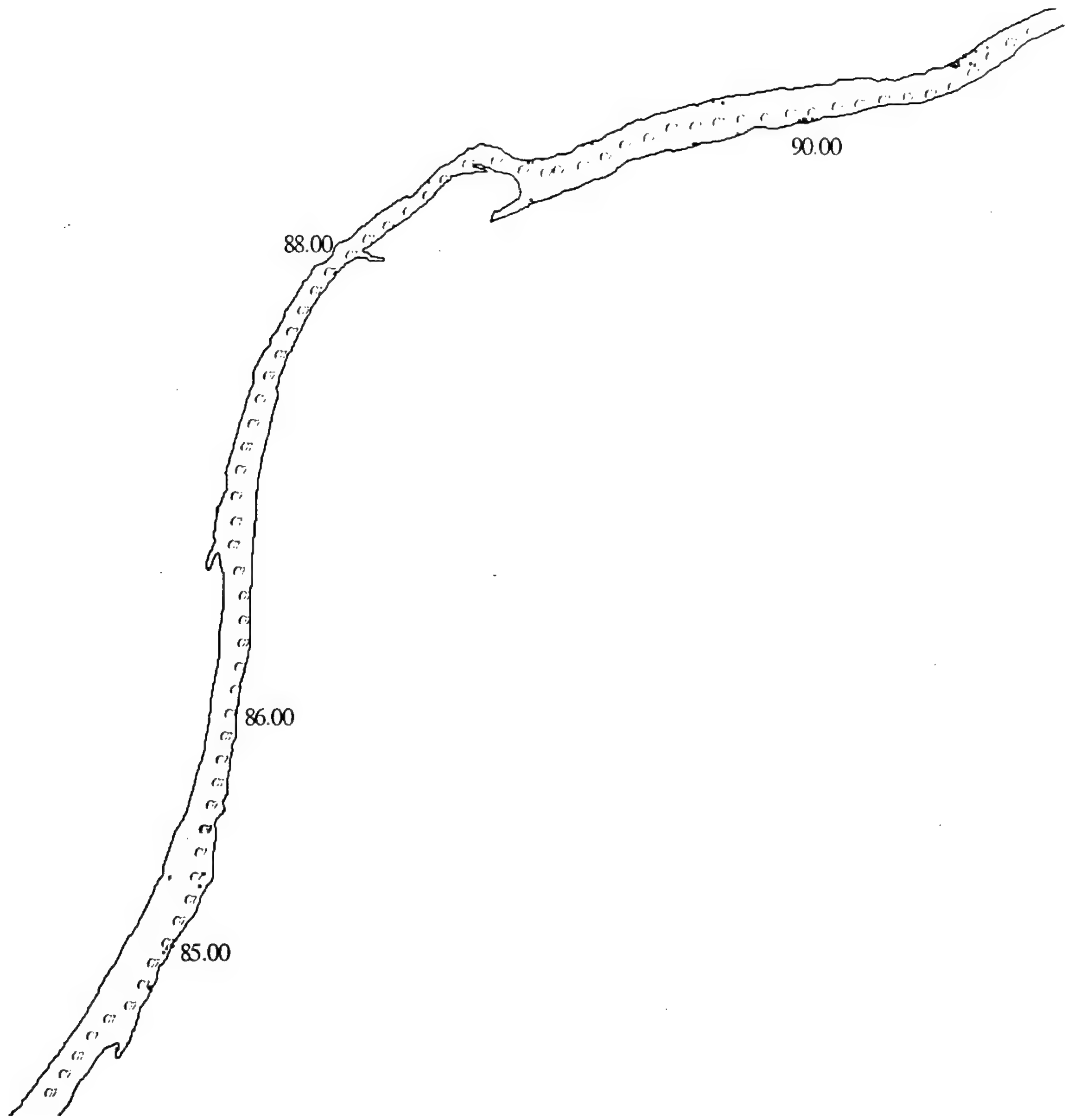


Figure 4-5. Example of Meandering Filament of Maximum Velocity

The level 2 classification resulted in 20 classes, including 4 within the level 1 class C_{bi}, 8 within F_{bi}, and 8 within F (Table 4-2). Again, most alluvial or partially-alluvial reaches fall under the level 1 classes, C_{bi} and F_{bi}, while bedrock-confined and colluvial reaches are found mostly in the areas of level 1 F classifications. The level 2 class $F_{bi}7$ represents the most common reach type, followed by F6, $C_{bi}4$, and $F_{bi}5$ (Table 4-3 and Figure 4-6). Level 2 classifications for each cross section are depicted spatially on Figures 4-7, 4-8, and 4-9, according to level 1 class C_{bi}, F_{bi}, and F, respectively. On a dam-by-dam basis, the section between Little Goose Dam and Lower Granite Dam contains the largest number and percentage (100 percent) of partially-alluvial reaches (Table 4-4). Similarly, the section upriver of Lower Granite Dam contains a considerable percentage of partially-alluvial (62 percent) and alluvial (20 percent) reaches (Table 4-4), particularly near the confluence with the Clearwater River.

Table 4-2. Level 2 Classification Descriptions by Level 1 Classification

Level 1	Level 2	Level 2 Code	Description
C_bi			The major lithology is dominated by unconsolidated sedimentary rocks and deposits. The river channel is moderately confined by the valley/canyon walls, indicating it is neither totally confined nor totally unconfined. Bars and/or islands are present.
	C_bi D34 F+ S+ ER+	C_bi1	Cobble/gravel substrate, moderate to high F, moderate to high slope, moderately entrenched.
	C_bi D34 F+ S+ ER-	C_bi2	Cobble/gravel substrate, moderate to high F, moderate to high slope, entrenched.
	C_bi D34 F+ S- ER+	C_bi3	Cobble/gravel substrate, moderate to high F, low slope, moderately entrenched.
	C_bi D34 F+ S- ER-	C_bi4	Cobble/gravel substrate, moderate to high F, low slope, entrenched.
F_bi			The major lithology is a mix of unconsolidated sedimentary rocks/deposits and basalt bedrock. The river channel is moderately confined by the valley/canyon walls, indicating it is neither totally confined nor totally unconfined. Bars and/or islands are present.
	F_bi D1 F+ S+ ER-	F_bi1	Bedrock channelbed, moderate to high F, moderate to high slope, entrenched.
	F_bi D1 F+ S- ER+	F_bi2	Bedrock channelbed, moderate to high F, low slope, moderately entrenched.
	F_bi D1 F+ S- ER-	F_bi3	Bedrock channelbed, moderate to high F, low slope, entrenched.
	F_bi D34 F+ S+ ER+	F_bi4	Cobble/gravel substrate, moderate to high F, moderate to high slope, moderately entrenched.
	F_bi D34 F+ S+ ER-	F_bi5	Cobble/gravel substrate, moderate to high F, moderate to high slope, entrenched.
	F_bi D34 F+ S- ER+	F_bi6	Cobble/gravel substrate, moderate to high F, low slope, moderately entrenched.
	F_bi D34 F+ S- ER-	F_bi7	Cobble/gravel substrate, moderate to high F, low slope, entrenched.
	F_bi D34 F- S- ER-	F_bi8	Cobble/gravel substrate, low F, low slope, entrenched.
F			The major lithology is a mix of unconsolidated sedimentary rocks/deposits and basalt bedrock. The river channel is highly confined by the valley/canyon walls, and occupies almost the entire valley bottom. Bars and/or islands are absent.
	F D1 F+ S+ ER-	F1	Bedrock channelbed, moderate to high *F*, moderate to high slope, entrenched.
	F D1 F+ S- ER+	F2	Bedrock channelbed, moderate to high *F*, low slope, moderately entrenched.
	F D1 F+ S- ER-	F3	Bedrock channelbed, moderate to high *F*, low slope, entrenched.
	F D34 F+ S+ ER-	F4	Cobble/gravel substrate, moderate to high *F*, moderate to high slope, entrenched.
	F D34 F+ S- ER+	F5	Cobble/gravel substrate, moderate to high *F*, low slope, moderately entrenched.
	F D34 F+ S- ER-	F6	Cobble/gravel substrate, moderate to high *F*, low slope, entrenched.
	F D34 F- S- ER+	F7	Cobble/gravel substrate, low *F*, low slope, moderately entrenched.
	F D34 F- S- ER-	F8	Cobble/gravel substrate, low *F*, low slope, entrenched.

Table 4-3. Level 2 Classifications as Percent of Lower Snake River

Level 2 Classification	Percent of Total
F_bI7	39.3
F6	18.9
C_bi4	10.7
F_bI5	8.6
F_bI6	8.0
F_bI4	2.7
F4	2.7
C_bi3	2.1
F1	1.8
F5	1.2
C_bi2	0.9
F3	0.6
C_bi1	0.3
F_bi1	0.3
F_bi2	0.3
F_bi3	0.3
F_bi8	0.3
F2	0.3
F7	0.3
F8	0.3

Table 4-4. Level 2 Classifications as Percent of Lower Snake River Segments

	Percent of Cross Section in Each Segment				
Level 2 Class	Mouth to Ice Harbor	Ice Harbor to Lower Monumental	Lower Monumental to Little Goose	Little Goose to Lower Granite	Upriver of Lower Granite
C_bi1	0.0	0.0	0.0	0.0	2.4
C_bi2	0.0	0.0	0.0	0.0	3.5
C_bi3	0.0	0.0	0.0	0.0	8.2
C_bi4	100.0	18.8	0.0	0.0	5.9
F1	0.0	0.0	8.3	0.0	1.2
F2	0.0	0.0	1.7	0.0	0.0
F3	0.0	0.0	3.3	0.0	0.0
F4	0.0	4.7	10.0	0.0	0.0
F5	0.0	0.0	5.0	0.0	0.0
F6	0.0	21.9	45.0	0.0	12.9
F7	0.0	0.0	1.7	0.0	0.0
F8	0.0	1.6	0.0	0.0	0.0
F_bi1	0.0	0.0	0.0	0.0	1.2
F_bi2	0.0	0.0	0.0	0.0	1.2
F_bi3	0.0	0.0	0.0	0.0	1.2
F_bi4	0.0	0.0	0.0	6.7	2.4
F_bi5	0.0	14.1	0.0	10.7	8.2
F_bi6	0.0	12.5	1.7	14.7	5.9
F_bi7	0.0	26.6	23.3	68.0	45.9
F_bi8	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0

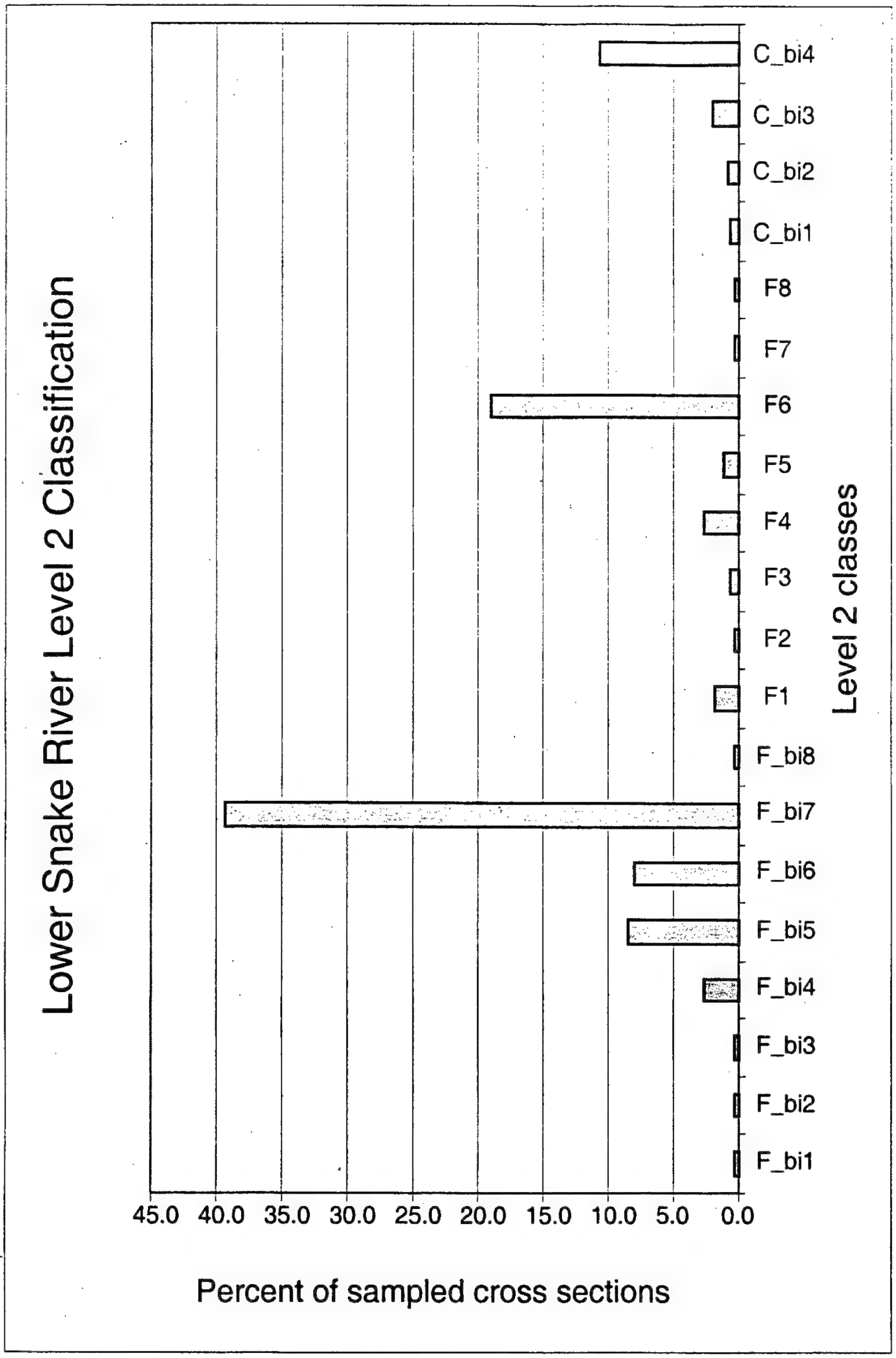


Figure 4-6. Level 2 Classifications as a Percent of the Lower Snake River

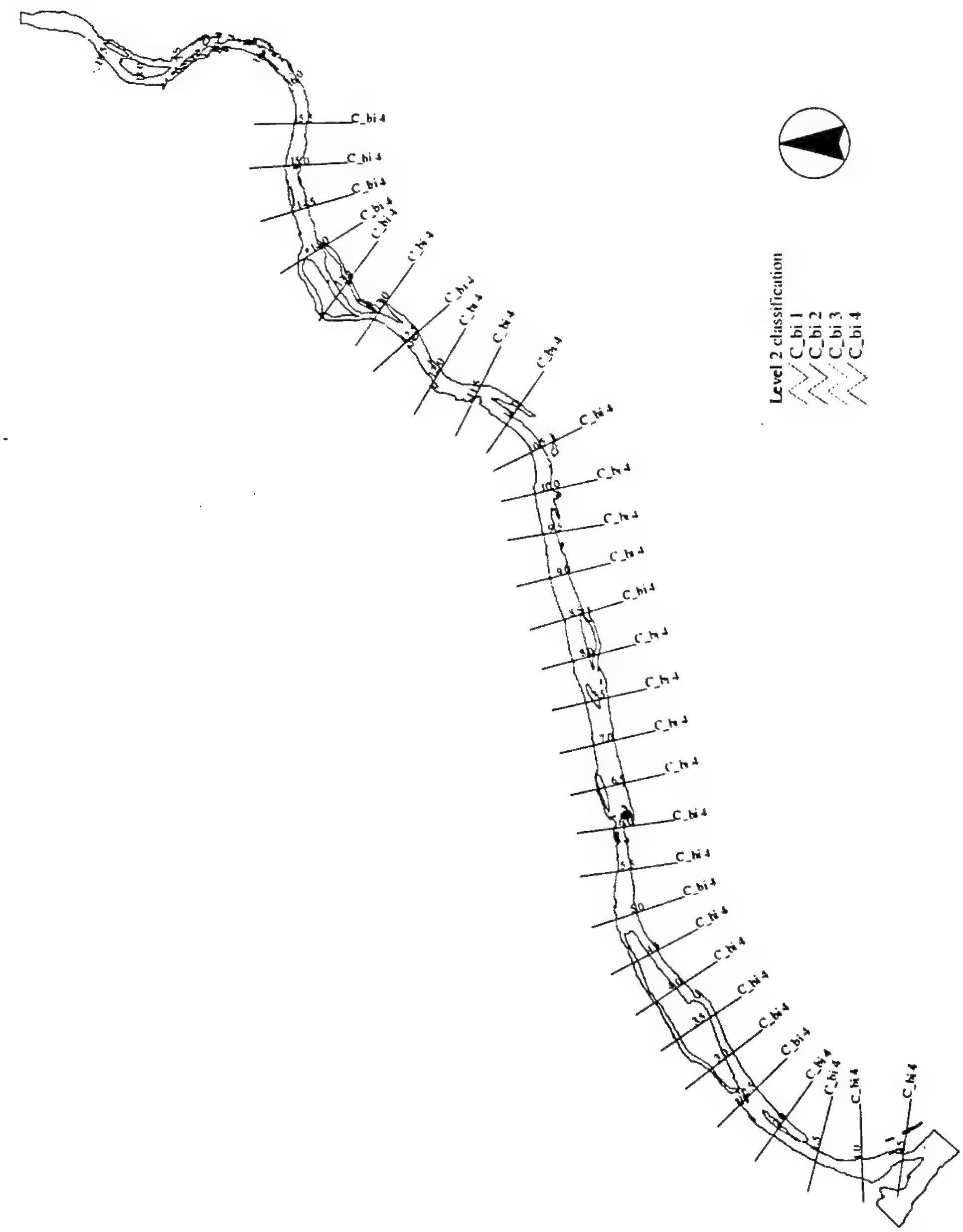


Figure 4-7. Level 2 C_{bi} Classification

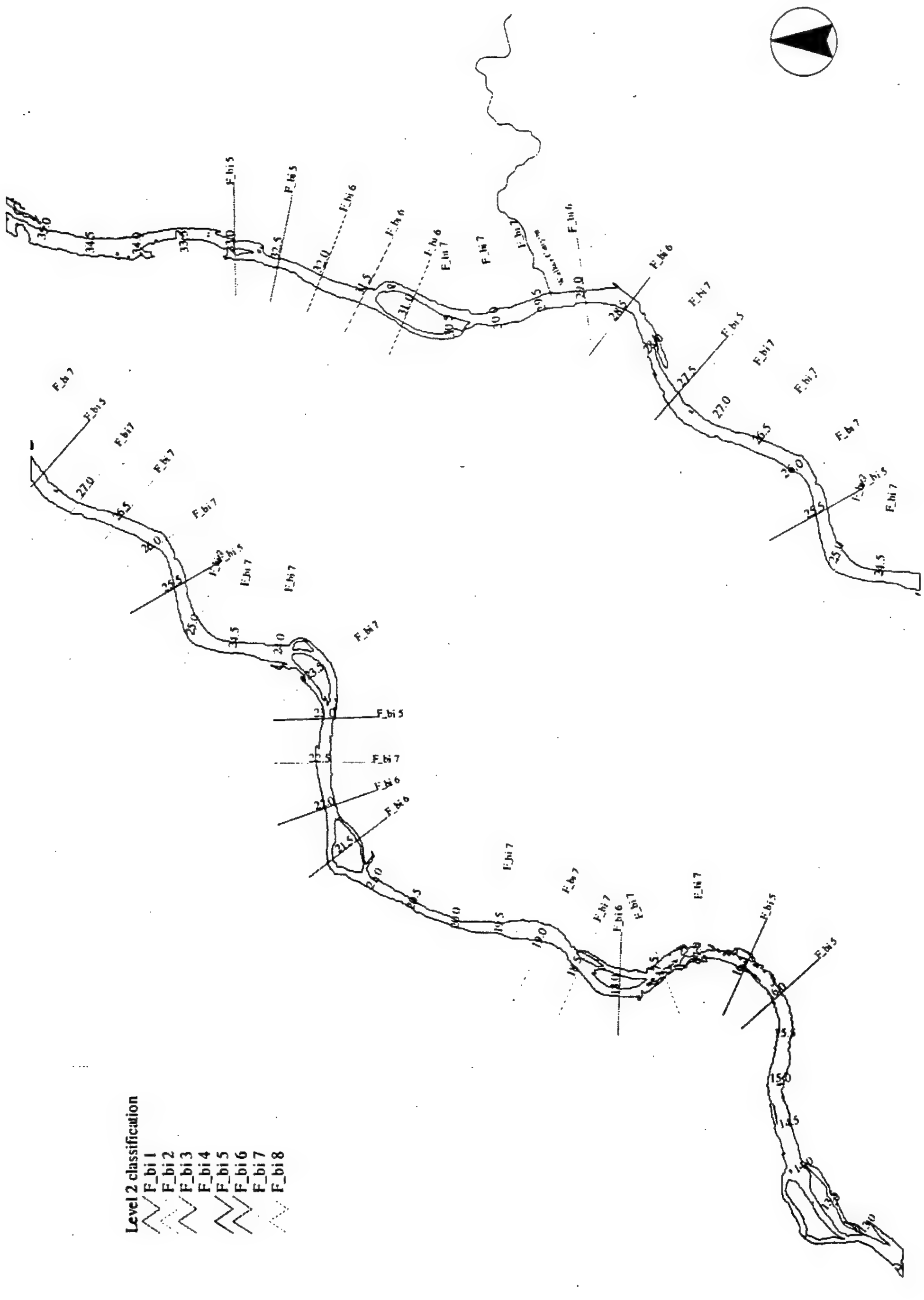


Figure 4-8. Level 2 F_{bi} Classification

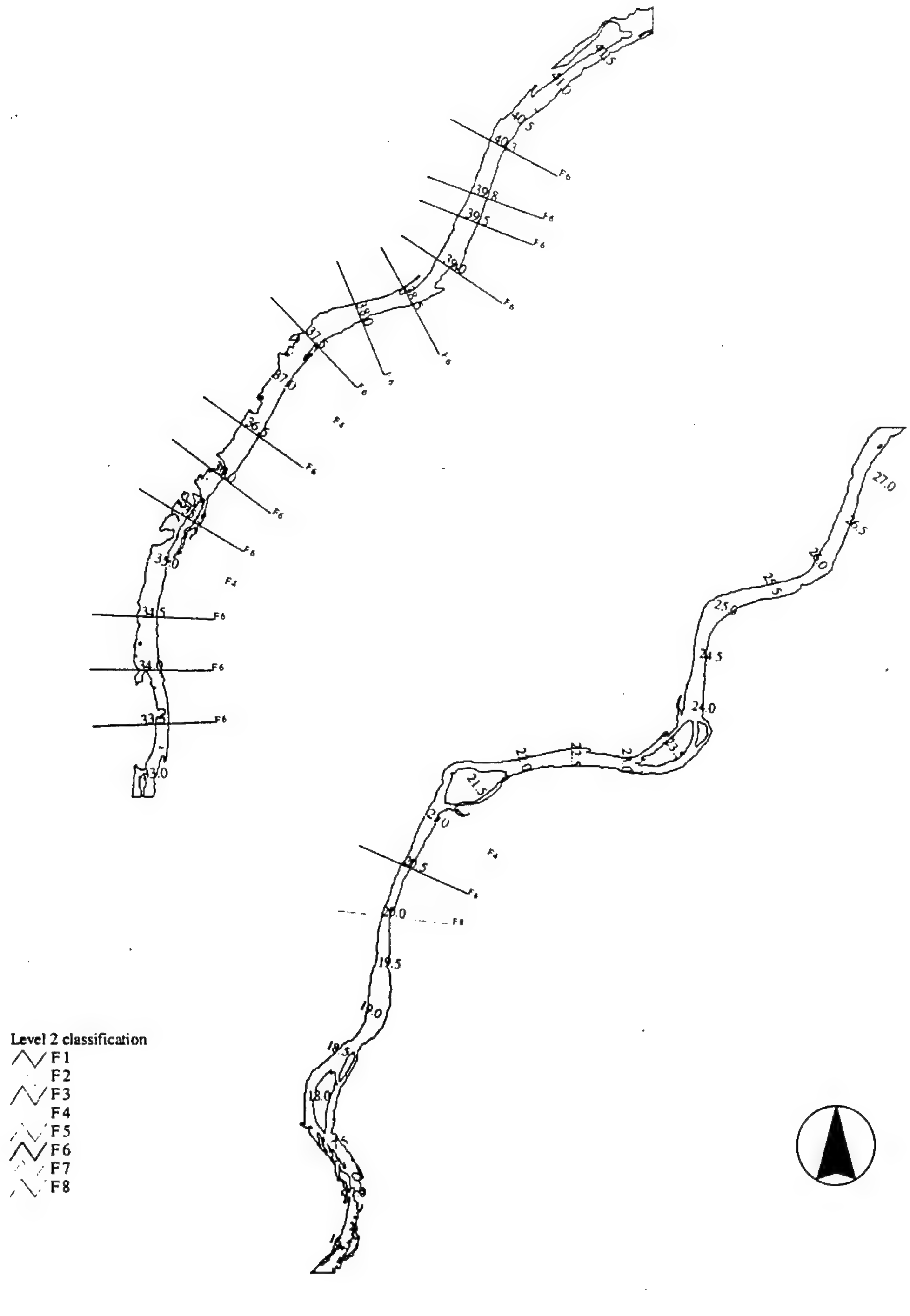


Figure 4-9. Level 2 F Classification

4.3 Additional Hydraulic and Geomorphic Characteristics

Mean velocity and mean depth for the Q50 flow provide an indication of hydraulic conditions from cross section to cross section (Figure 4-10), including indications of pools and riffles. Unit stream power is a hydraulic parameter often used to describe a river's ability to transport sediment and perform geomorphic work (Bagnold, 1977; Richards, 1982; Thorne, 1997). Stream power per unit bed area (ω) ranges from approximately 0 to 150 Watts m-2, oscillating in magnitude between river reaches (e.g., Figure 4-11). The oscillations in ω, closely match the oscillations of the longitudinal bedform profile. When plotted with the water surface elevation at cross sections spaced 0.16 km (0.1 mi) apart, the longitudinal bedform profile is indicative of alternating pool/riffle channel morphology (Figure 4-12). Riffle spacing in straight alluvial rivers has been described as being fairly constant—between 5 to 7 channel widths apart (Leopold et al., 1964). Research on gravel- and cobble-bed rivers in England found a similar pattern, with riffle spacing ranging from 4 to 10 channel widths in length (Hey and Thorne, 1986). In many segments of the study area the riffle spacing ranges from 4 to 10 channel widths in length (Figure 4-12). This characteristic of non-uniform bed topography in a straight alluvial channel is indicative of sufficiently widely graded bed material such that selective entrainment, transport, and deposition produces systematic sorting of grain sizes between scour pools and riffle bars (Thorne, 1997).

Based on velocity:depth criteria given earlier, the pre-dam channel morphology and the Q_{50} flow, the lower Snake River contained 4,060 hectares (ha) (10,032 acres) of pool habitat, 1,792 ha (4 ,428 acres) of run habitat, and 279 ha (689 acres) of riffle/rapid habitat (e.g., Figure 4-13). On a dam-by-dam basis, the section upriver of Lower Granite Dam contains the greatest percentage (70.5 percent) of pool habitat (Table 4-5). The section between Little Goose Dam and Lower Granite Dam contains the greatest surface area of pool habitat (970 ha [2397 acres]; 64 percent), while the section between Lower Monument Dam and Little Goose Dam is characterized by more riffle/rapid and run habitat (Table 4-5). These habitat features are very generalized, as there are many variations within a particular habitat class (e.g., mid-channel pool, backwater pool). Even on the rivers where the criteria were calibrated, correct classification of habitat features is only moderately accurate. For example, in a study with extensive field-calibrated data, Jowett (1993) was only able to correctly classify 65 percent of the habitats. Additionally, the amount of pool habitat downriver of Ice Harbor Dam may be overestimated because the hydraulic model incorporates the reservoir elevation backwater effects near the Columbia River confluence caused by McNary Dam.

The cross sectional form of natural channels are characteristically irregular and locally variable (Knighton, 1984). The width to depth ratio (F) is an important indicator of the distribution of available energy within a channel, and the ability of various discharges to move sediment (Rosgen, 1996). Relatively high F values such as those in the pre-dam lower Snake River (Figure 4-12) are often indicators of channel instability. This indication is based on the fact that channels with high F values distribute energy and stress on the near-bank region (Rosgen, 1996). Whether a reach with high F values is indeed unstable depends on the erosion resistance characteristics of the bank material. Bank materials in the lower Snake River are predominantly highly erosion resistant.

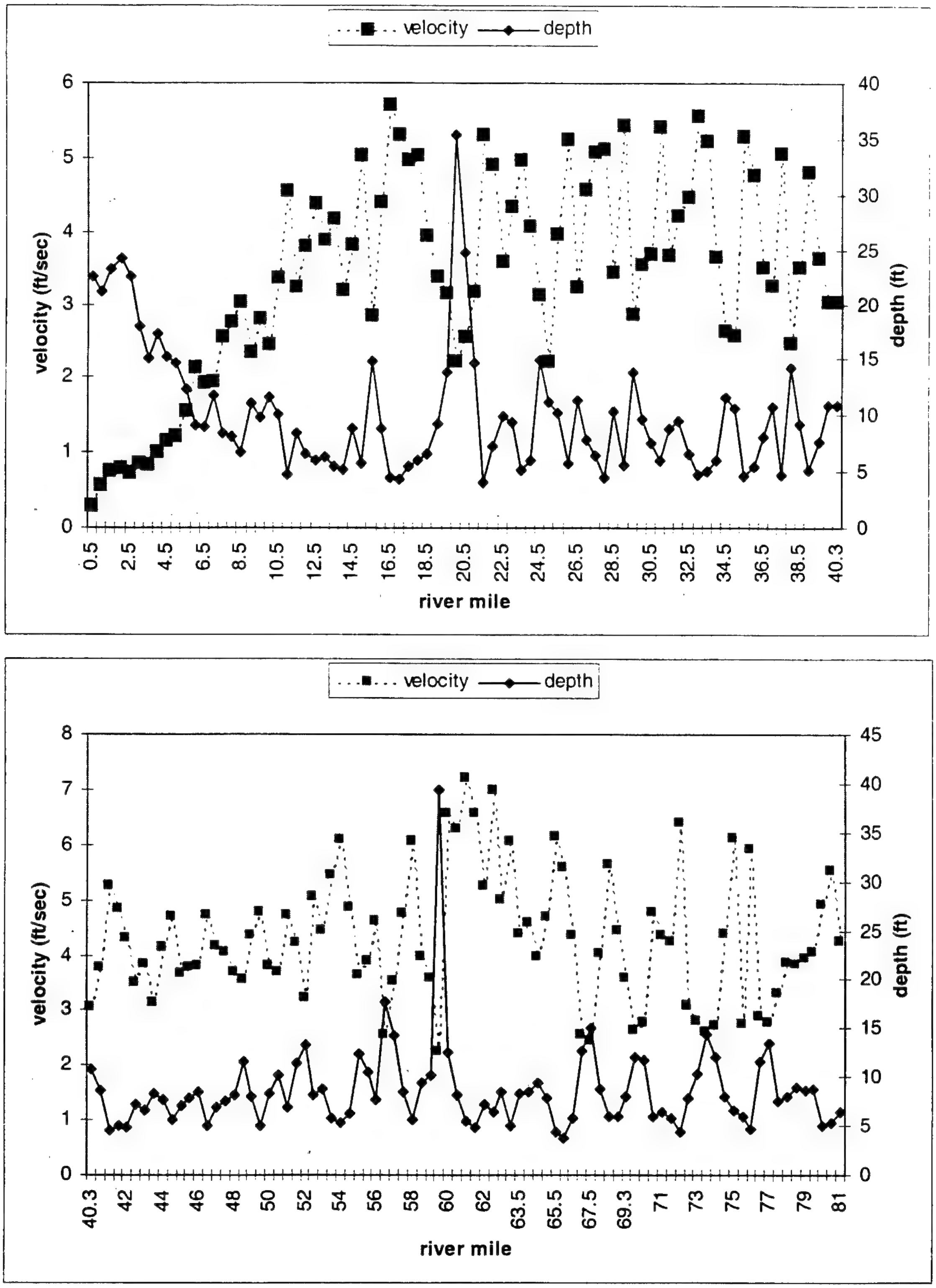
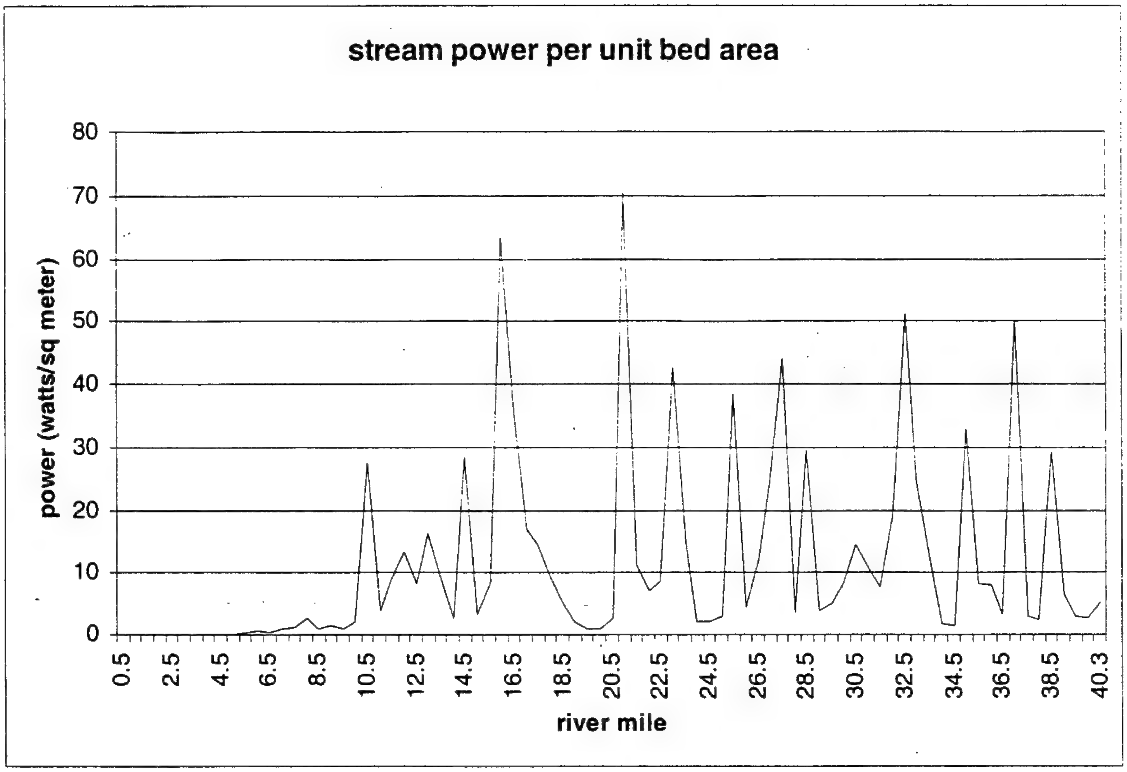


Figure 4-10. Mean Velocity and Mean Depth at Each Cross Section for Q_{50} Flow



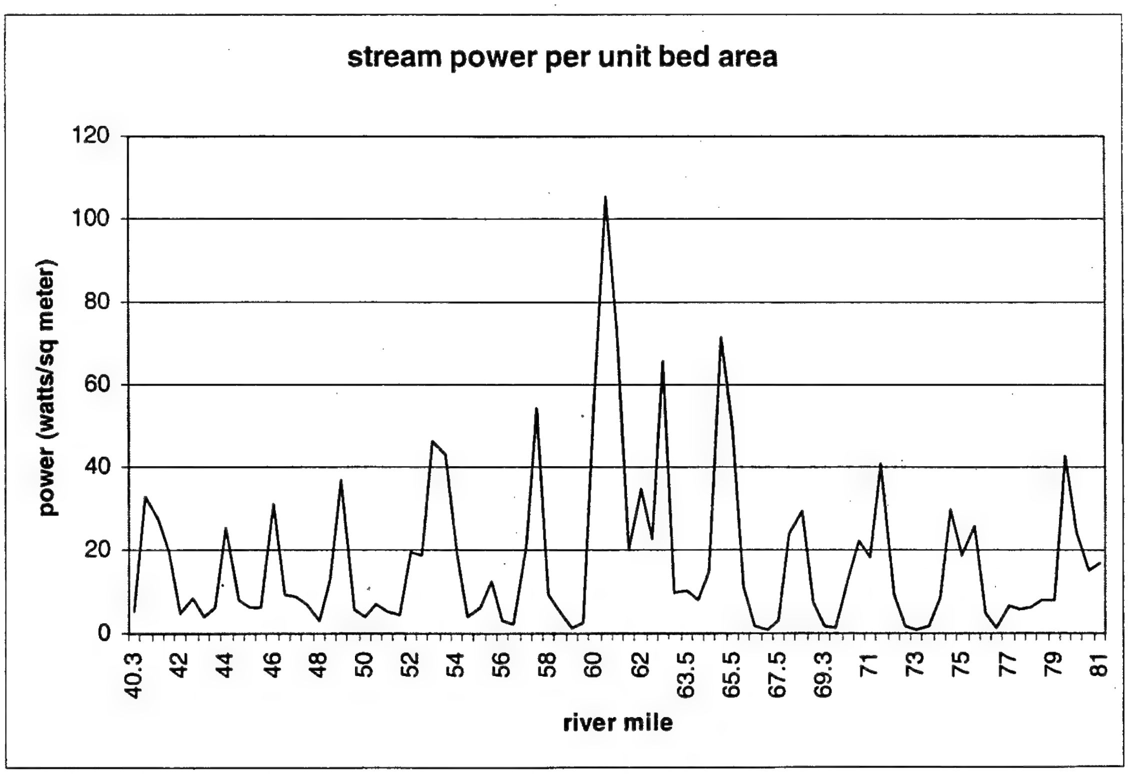
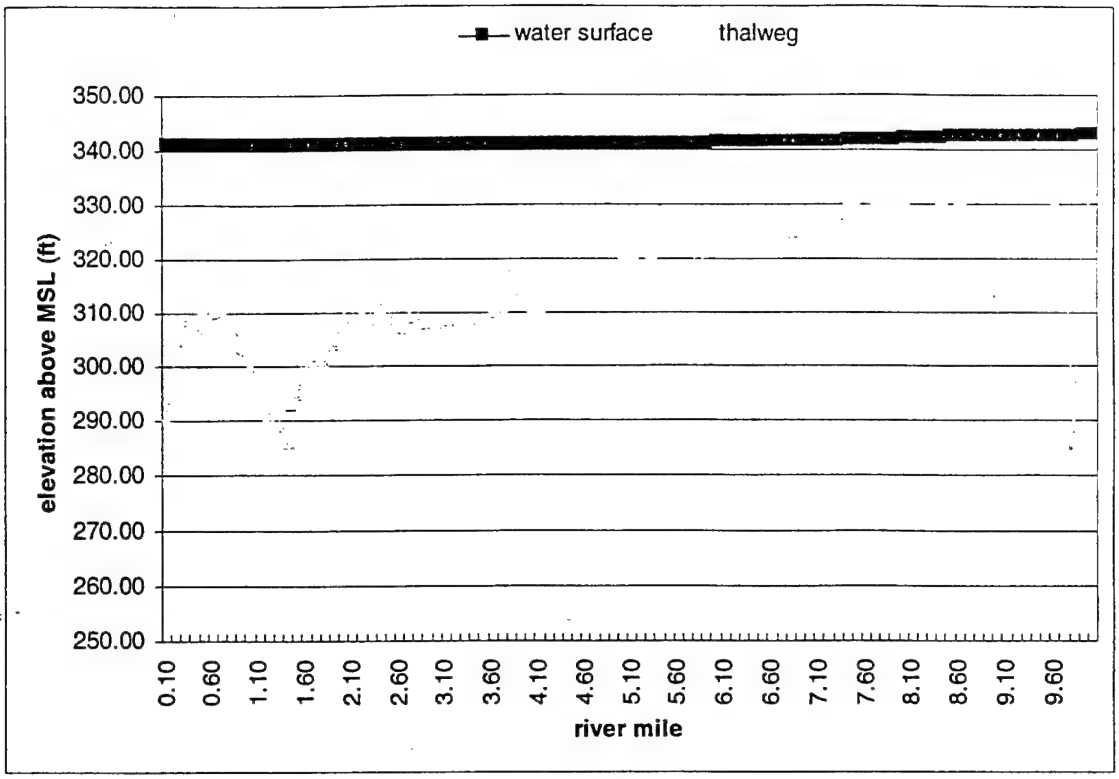


Figure 4-11. Stream Power at Each Cross Section for Q_{50} Flow



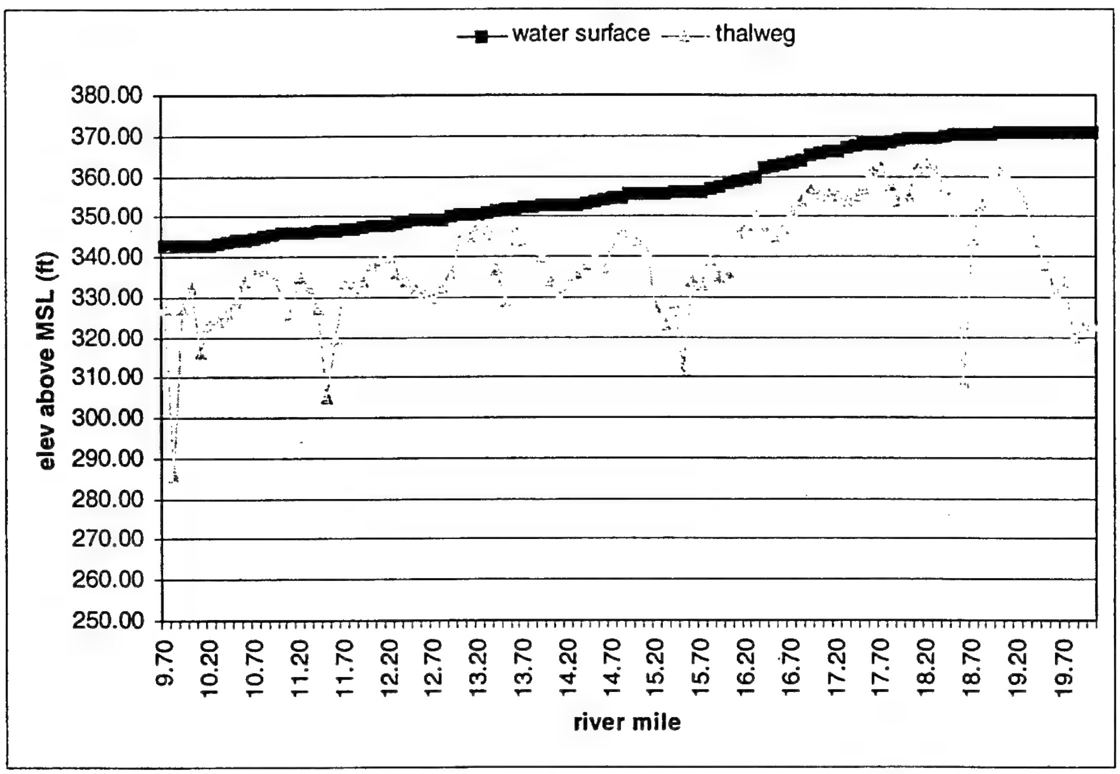


Figure 4-12. Longitudinal Profile of Water Surface and Thalweg Elevations for Q_{90} Flow

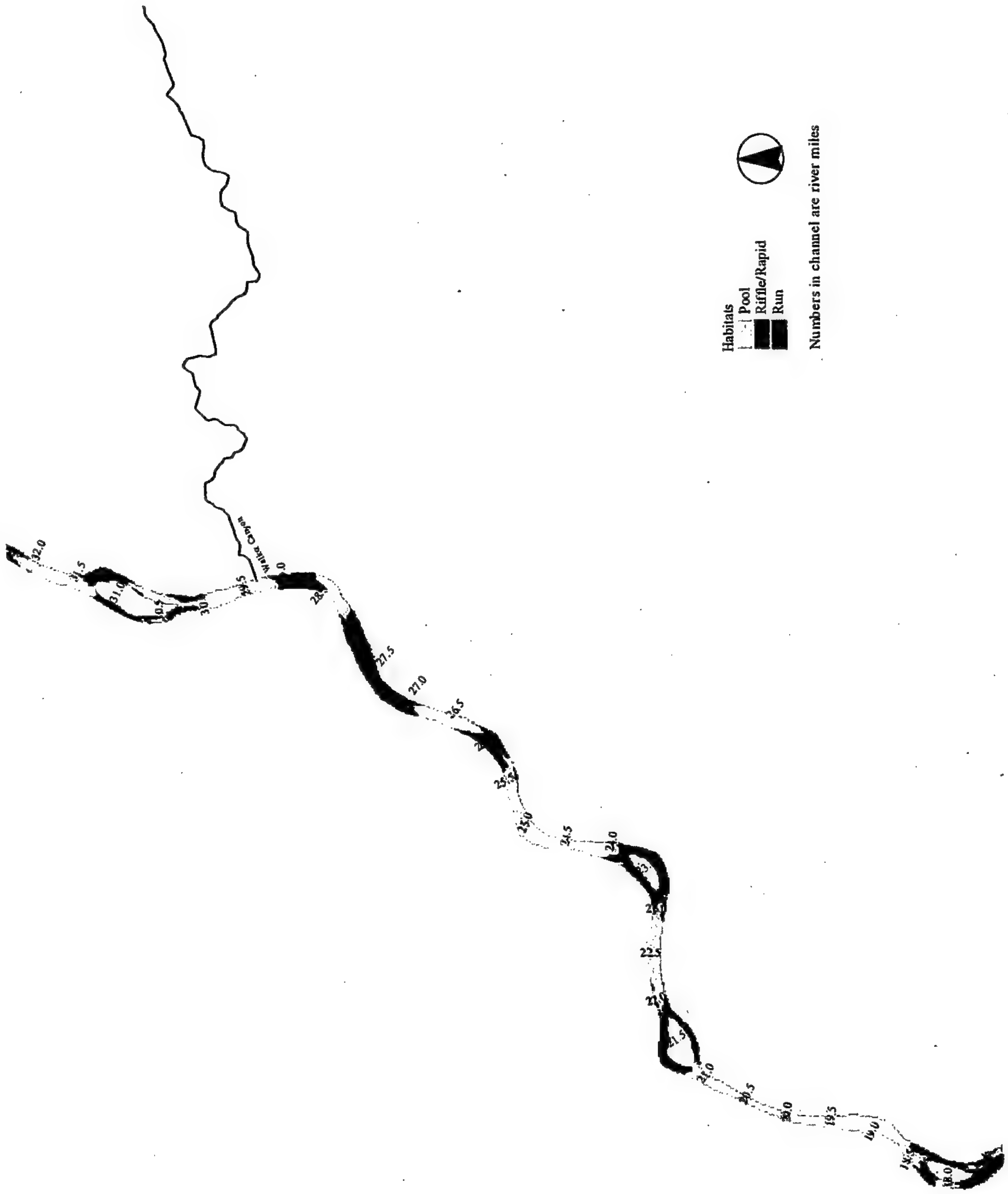


Figure 4-13. Pool, Run, and Riffle/Rapid Habitats

Table 4-5. Pool, Riffle/Rapid, Run Habitats of Lower Snake River Segments

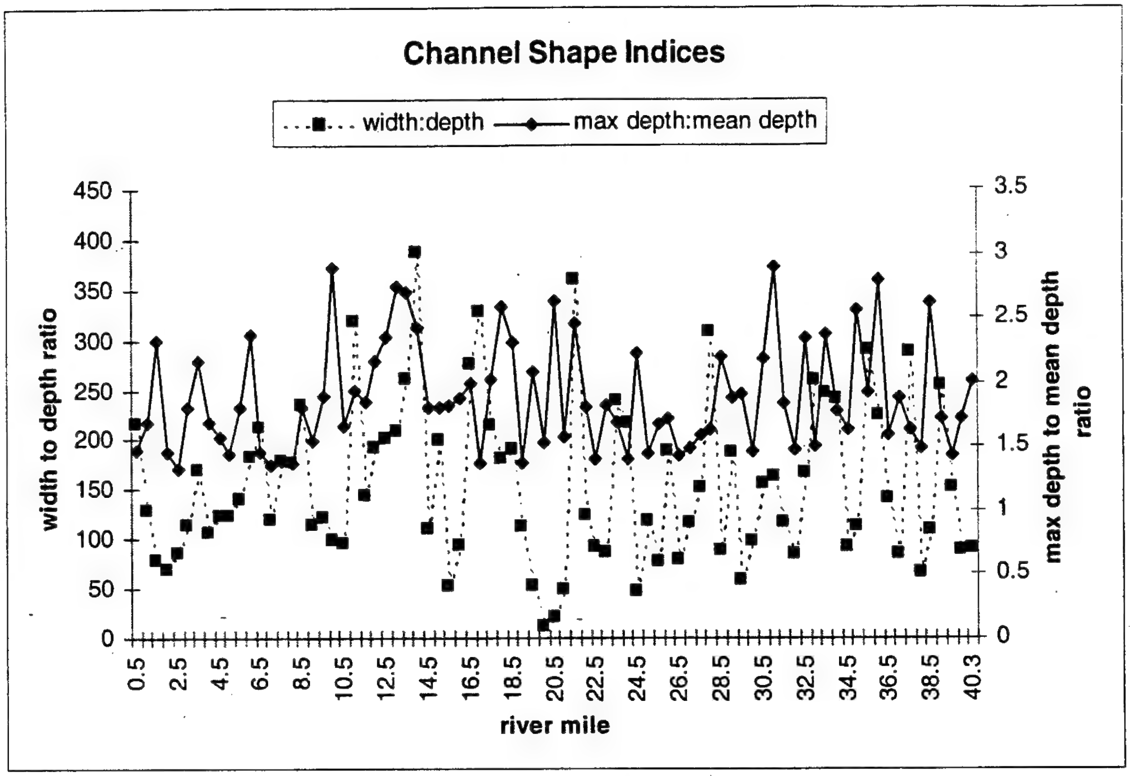
Segment	Habitat by Segments – Hectares (%)			
	Pool	Riffle/Rapid	Run	Total
Mouth to Ice Harbor	791.9 (97.7)	0.0 (0.0)	18.7 (2.3)	810.6 (100)
Ice Harbor to Lower Monumental	839.0 (57.5)	97.6 (6.7)	521.7 (35.8)	1458.3 (100)
Lower Monumental to Little Goose	694.8 (55.0)	72.1 (5.7)	495.8 (39.3)	1262.8 (100)
Little Goose to Lower Granite	970.2 (64.0)	72.9 (4.8)	471.9 (31.1)	1515.0 (100)
Upriver of Lower Granite	764.1 (70.5)	36.6 (3.4)	283.4 (26.1)	1084.1 (100)
Total	4060.0 (66.2)	279.2 (4.6)	1791.5 (29.2)	6130.7 (100)

The d_{max}/d parameter is an index of channel asymmetry. Channels with a d_{max}/d value approaching 1 are trapezoidal and regular in shape, while higher values indicate bedform diversity within a cross section. The cross sections in the pre-dam lower Snake River indicate variable d_{max}/d values, with lower values roughly corresponding to lower F values (Figure 4-14). The latter observation is indicative of narrow, deep river reaches that are trapezoidal in shape. A final parameter describing the variability in natural channels is the planform characteristic of top width. Top width was calculated at each cross section, based on the Q_{50} flow. Top widths in the study area were highly variable from cross section to cross section (Figure 4-15), indicating planform channel asymmetry.

4.4 Geomorphic Features and Salmon Production Areas

Redd density data is not available for fall chinook spawning in the lower Snake River. Such information has, however, been well documented for the remainder of the Snake River during most of the hydro development period (Battelle and USGS, 1999), and provided a means to evaluate the relationship of various geomorphic features and spawning density in the Snake River.

When we applied the geomorphic spawning habitat model to the lower Snake River (from the mouth upriver to Tenmile Rapids at rkm 238.5 (rm 148)—the upper limit of present day Lower Granite Dam reservoir), we estimated approximately 131 km (81 mi) of suitable spawning habitat may have been available during the pre-hydroelectric development period. This distance represents approximately 55 percent of the lower Snake River. In contrast, historical accounts of fall chinook spawning locations indicate that approximately 51 km (32 mi; 21 percent) of the lower Snake River was used as spawning habitat. Explaining the differences between these estimates is confounded by the quality and scarcity of historic spawning records for the lower Snake River. The historic records used were based on one account of estimated lineal river distance used for spawning, rather than repeated surveys, and may therefore be an underestimate. In a similar analysis for the remainder of the mainstem Snake and Columbia Rivers, the geomorphic model predicted 40 to 50 percent less suitable spawning habitat than what was actually documented to occur (Battelle and USGS, 1999).



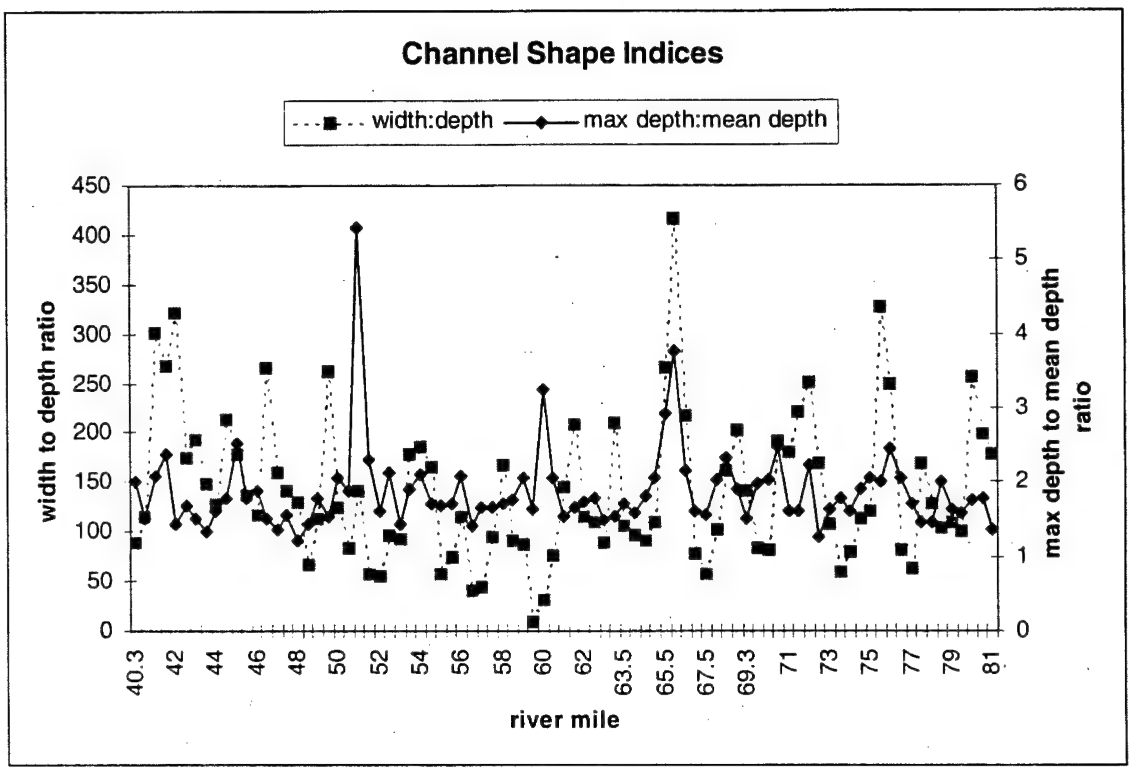
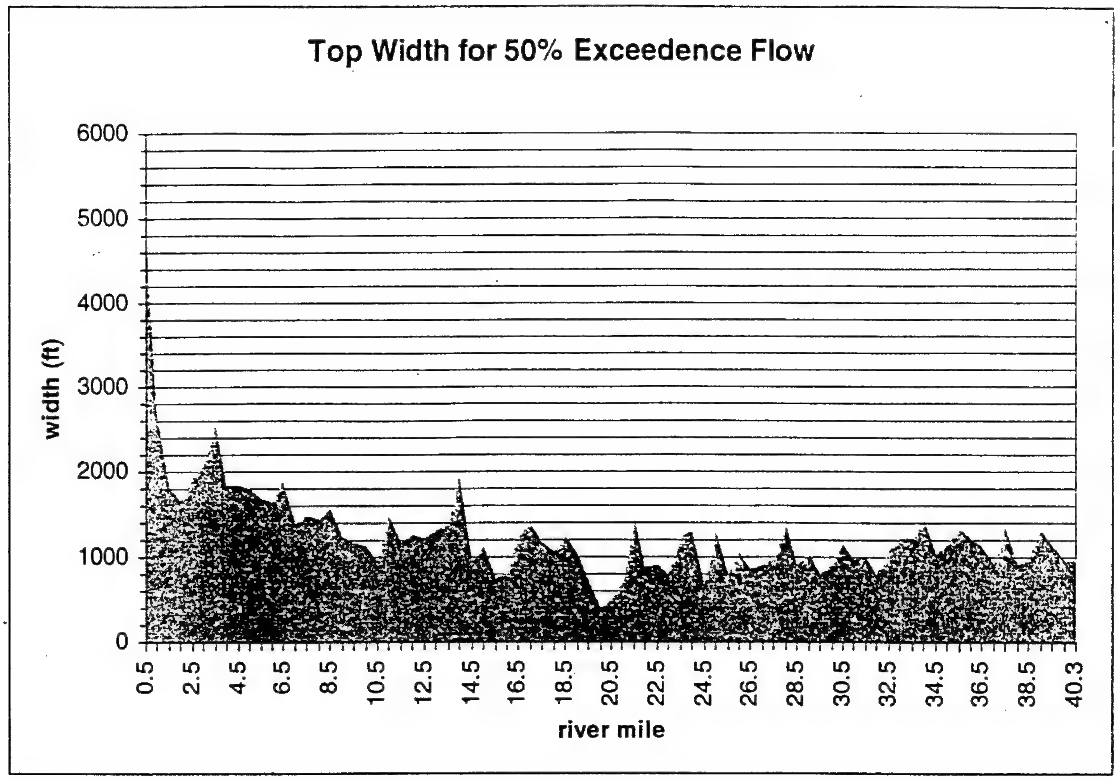


Figure 4-14. Channel Shape Indices at Each Cross Section for Q_{50} Flow



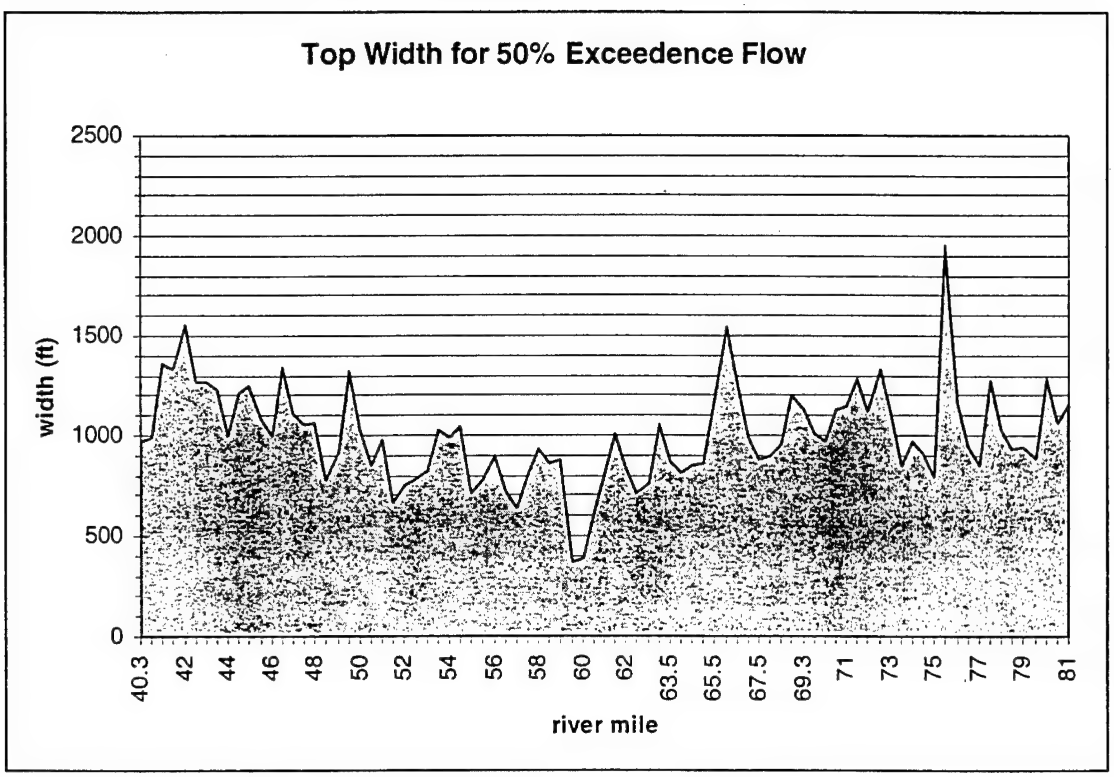


Figure 4-15. Top Width at Each Cross Section for Q_{50} Flow

Historical accounts of fall chinook spawning include the area from rkm 11 to 30 (rm 7 to 19; currently Ice Harbor Dam vicinity), from rkm 96-128 (rm 60 to 80; upstream of the Palouse River;), and near the confluence of the Clearwater River (Figure 4-16). The geomorphic model suggests that approximately 87 percent of the lineal river distance from Little Goose Dam upriver to Lower Granite Dam contains geomorphic characteristics conducive to fall chinook spawning (Table 4-6; Figure 4-16), or the largest portion of potentially suitable fall chinook spawning habitat on a dam-by-dam basis.

Table 4-6. Geomorphic Spawning Habitat Model Prediction for Lower Snake River Sections

Section	Section Length (km)	Modeled Spawning Suitability (km)	Percent of Section
Mouth to Ice Harbor	15.5	15.5	100.0
Ice Harbor to Lower Monumental	50.5	28.5	56.4
Lower Monumental to Little Goose	46.5	7.0	15.1
Little Goose to Lower Granite	59.5	52.0	87.4
Lower Granite to 10 mile Rapids	66.5	28.0	42.1
Lower Snake Total	238.5	131.0	54.9

The results of our geomorphic model were different than estimates of fall chinook spawning habitat based on traditional modeling characteristics of suitable depth, velocity, and substrate (USFWS, 1999). The USFWS (1999) recently estimated that the section from Lower Monument Dam to Little Goose Dam had the most potential spawning habitat under dam breaching (Table 4-7).

Table 4-7. Fall Chinook Spawning Habitat (Percent) Under Natural River Conditions Based on Modeled Depths, Velocities, and Substrates (USFWS, 1999)

Suitability	Location					
	Mouth to Ice Harbor	Ice Harbor to Lower Monumental	Lower Monumental to Little Goose	Little Goose to Lower Granite	Upriver of Lower Granite	Total
Not suitable	63.7	57.2	39.2	79.9	92.3	66.6
Suitable	32.9	31.0	40.7	12.2	2.8	23.5
Unknown	3.5	11.8	20.2	7.9	4.9	10.3

The geomorphic model helps refine where fall chinook salmon would spawn, however estimating surface area of a section of river used for spawning (microhabitat scale) requires the inclusion of finer-scale geomorphic variables. This scaling discrepancy is evident at the Hanford Reach of the Columbia River, where we have an extensive dataset of fine-scale fall chinook spawning locations and density. The geomorphic model predicts 66.5 km (41 mi; 67 percent) of suitable spawning habitat in the Hanford Reach. The surface area actually used for redds (based on aerial surveys [Dauble and Watson, 1997] and underwater video) is only approximately 5 percent.

4.5 Flow Regime and Sediment Transport

Historical discharge records provided a means of comparing pre-major storage flow regimes with post-major storage flow regimes to determine if the latter has a geomorphic competency similar to the former. The annual maximum discharge, pre- and post-major storage, has not changed much (Figure 4-17). The mean of pre-major storage period annual maximum discharge is 5,326 cms (188,087 cfs), while the mean for the post-major storage period is 4,793 cms (169,257 cfs; Table 4-8).

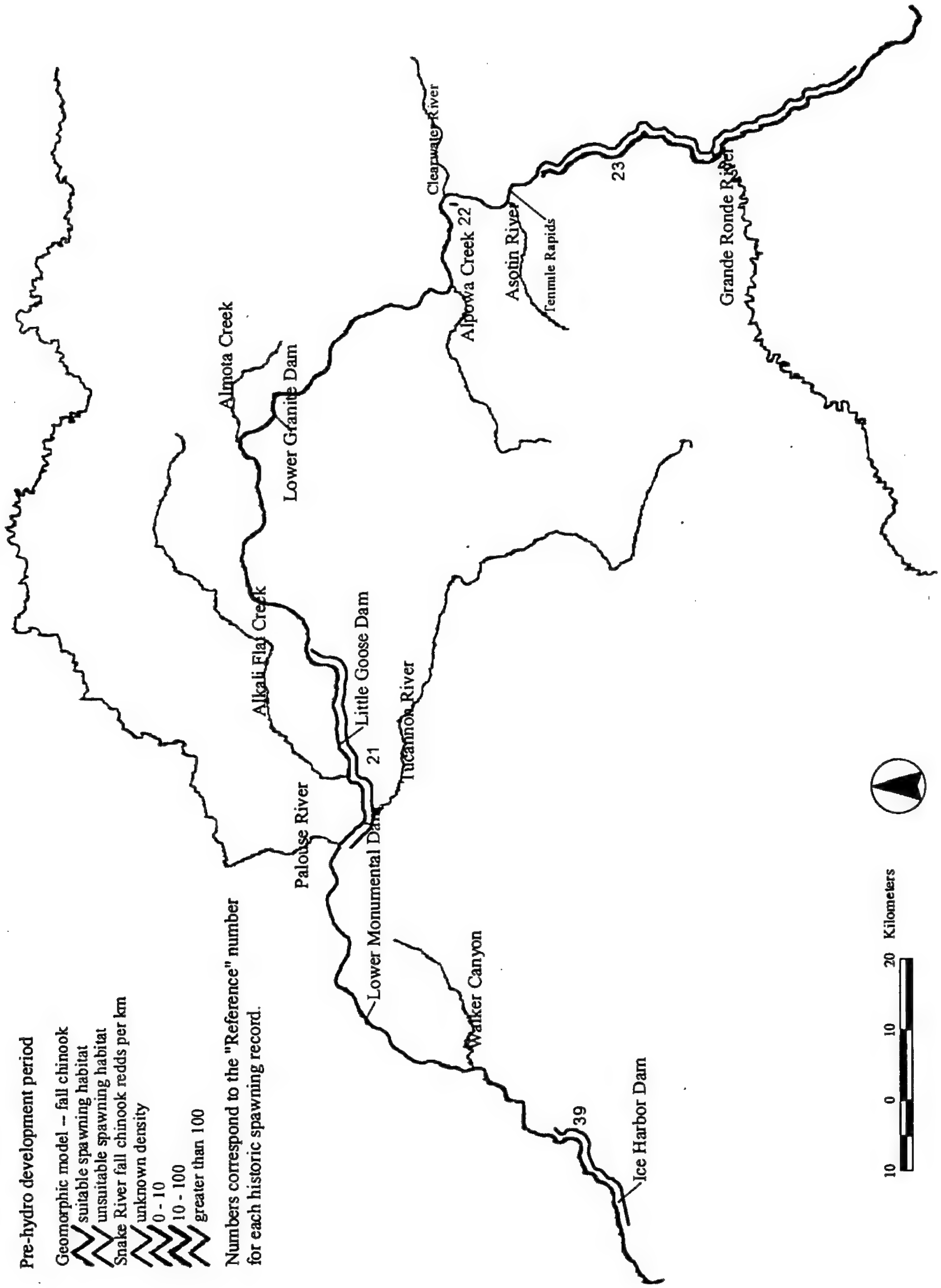


Figure 4-16. Geomorphic Spawning Habitat Model and Pre-hydro Development Period Fall Chinook Spawning Locations

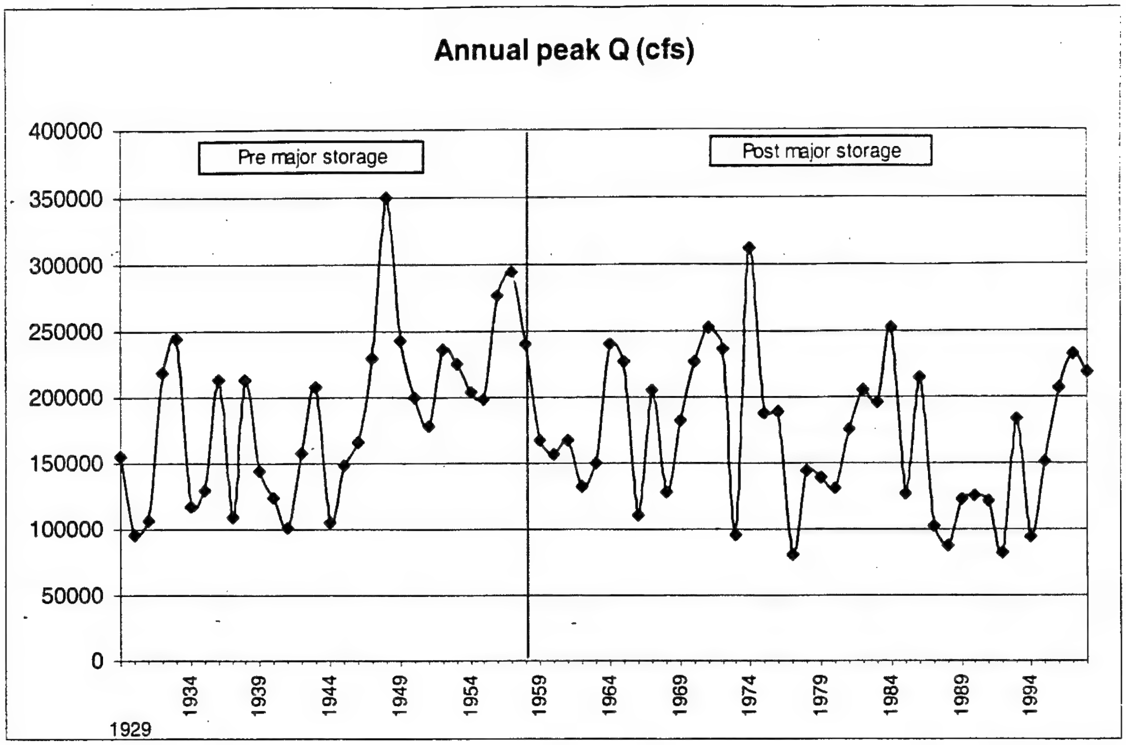


Figure 4-17. Lower Snake River Annual Peak Discharge, 1929 to 1998

Table 4-8. Lower Snake River Change in Annual Maximum Discharge for Pre- and Post-major Storage Periods (Units Are in cms [cfs])

	Pre-major Storage	Post-major Storage	Change	Post Percent of Pre-major Storage
Mean	5,326 (188,087)	4,793 (169,257)	533 (18,830)	90
Range	7,204 (254,400)	6,556 (231,539)	647 (22,861)	91
Minimum	2,707 (95,600)	2,290 (80,882)	417 (14,718)	85
Maximum	9,911 (350,000)	8,847 (312,421)	1,064 (37,579)	89

The geomorphic competency (erosional and depositional processes affecting morphological change) of a river is often determined by the bankfull flow (Hey, 1997). The return period of bankfull flow for gravel-bed rivers is commonly determined as the 1.0- to 2.0-year flood, based on the annual maximum series (Leopold et al., 1964; Williams, 1978). Because this method excludes lesser flood events above bed material transport thresholds, return periods based on partial duration series with a threshold discharge set at the initiation of bed material movement have been used as an alternative (Carling, 1988; Hey and Heritage, 1988; Hey, 1997). This method yields a return period once every 0.9 years for bankfull flow in UK gravel-bed rivers (Hey and Heritage, 1988; Hey, 1997). To compare pre- and post-major storage geomorphic competency, we set the threshold value at the pre-major storage 1.0-year flood, based on the annual maximum series. During the pre-major storage period this threshold discharge was equaled or exceeded 13 percent of the time. This percentage increased to 14 percent during the post-major storage period, suggesting no considerable difference in

the geomorphic competency between the two periods. On an annual basis, the number of days the threshold discharge was equaled or exceeded ranged from 1 to 100 and 0 to 121 during the pre- and post-major storage periods, respectively.

The frequency of occurrence of the threshold discharge during any given year is particularly important in evaluating the time period expected for remobilization of the lower Snake River channelbed surface. The flow required for initiation of bedload transport can be much higher than typical criteria for rivers with a prolonged period of no sediment transport, and containing infiltrated cohesive fine sediments that create a powerful cementation effect (Reid et al., 1997); conditions analogous to those in the impounded lower Snake River. During the first flood event following such conditions bedload transport may be minimal, but will increase during subsequent flood events occurring with greater frequency (Reid et al., 1985). Therefore, the time period required for critical transport conditions in the lower Snake River will depend to some extent on the number of days the threshold discharge is equaled or exceeded in each year following dam breaching. This frequency is subject to the natural variability of water year types, ranging from extremely wet to extremely dry.

The geomorphic competency of the lower Snake River under the dam breaching is also reflected in estimates of fine sediment transport. It was estimated that the majority of fine sediments accumulated in Lower Granite Reservoir would be eroded and transported within 5 years of the removal of Lower Granite Dam (Figure 4-18; Hanrahan et al., 1998). These estimates are in agreement with observations made during the 1992 drawdown test of Lower Granite Dam reservoir (Corps, 1993), and with modeled estimates of sediment mobility in the lower Snake River as a whole (Richmond et al., 1999).

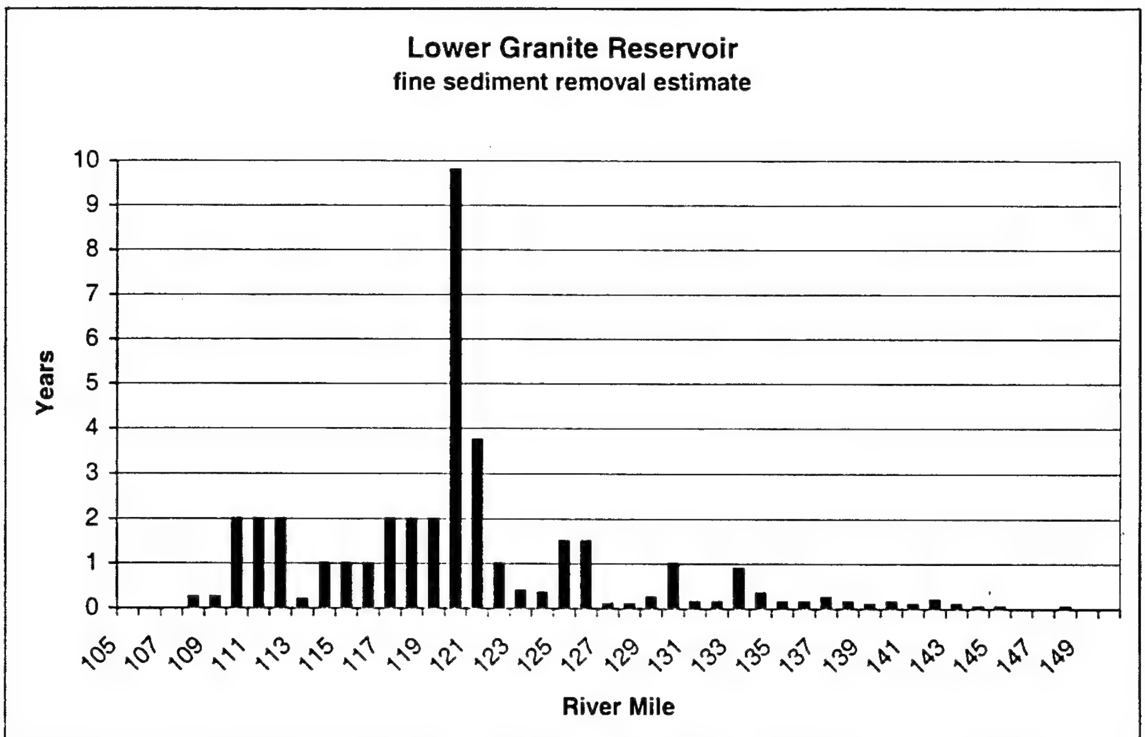


Figure 4-18. Estimated Time to Remove Fine Sediments From Lower Granite Reservoir Under Dam Breaching

5. Conclusions and Recommendations

Prior to impoundment, the lower Snake River exhibited heterogeneous characteristics ranging from those typical of alluvial reaches to those typical of bedrock-confined reaches in large rivers. In general, the pre-dam channel was a morphologically diverse, coarse-bedded, stable river possessing a meandering thalweg and classic pool-riffle longitudinal bedform profile.

The geomorphic model of fall chinook spawning habitat suggests that several alluvial and partially-alluvial reaches may be particularly important restoration areas. Two such areas within the lower Snake River are from the mouth upriver to approximately RKM 31 (RM 19), and near the confluence with the Clearwater River from RKM 215 to 229 (RM 134 to 142). One large contiguous section potentially suitable for fall chinook spawning extends from approximately RKM 106 to 193 (RM 66 to 120), which includes much of the Little Goose Reservoir.

Analysis of historic and contemporary discharge records indicates that regulated flow regimes after dam breaching would be competent enough to maintain channel characteristics and riverine processes (e.g., channelbed mobilization). The time required before the realization of these characteristics and processes depends on many interrelated factors, including an initial 5-year to 10-year period of erosion and transport of fine sediments accumulated in the reservoirs since dam construction. After the bulk of those fine sediments are removed, the competency of the regulated flow regime (particularly the annual maximum discharge) will be sufficient to mobilize the channelbed surface. The time required for the initiation of such processes depends on the annual flow regimes during the period following dam breaching, particularly the frequency and duration of annual maximum discharge equaling or exceeding the pre-major storage period 1-year flood of 2,707 cms (95,600 cfs).

The results of this study address several primary issues concerning breaching of the four lower Snake River dams, including: 1) understanding the physical characteristics of the pre-dam river; 2) determining the extent and location of pre-dam fall chinook spawning, as well as potential locations for post-drawdown fall chinook spawning; and 3) determining if the post-breaching flow regime is competent to maintain important geomorphic processes. The results provide a starting point for continued analyses of post-breaching fluvial geomorphology at a much finer scale.

The proposed breaching of the four lower Snake River dams can be viewed as an attempt to restore riverine conditions to what is currently a series of impounded reservoirs. The ultimate goal of this effort is the restoration of anadromous Snake River salmonid populations. The restoration of these populations arguably necessitates the recovery of a healthy river ecosystem (Stanford et al., 1996), not simply the restoration of habitat (e.g., suitable spawning depth, velocity, and substrate) for one or two species. The spatial and successional patterns of biological communities in river ecosystems are controlled by the abiotic attributes describing the hydrology, geomorphology, and water quality (Lorenz et al., 1997). Some of the essential abiotic attributes applying generally to alluvial and partially-alluvial rivers are listed in Table 5-1.

Table 5-1. Alluvial River Attributes [1/]

Attribute	Description	Ecological Significance
Spatially-complex channel morphology	Alternate bar morphology, m side channels and backwater areas, asymmetrical cross sections, etc.	Provides diverse salmonid habitat availability for all life stages over wide-ranging flows Supports diverse and productive biological communities Develops and maintains diverse riparian plant communities in all stages of succesional development
Natural variability in flows and water quality	Natural periodicity, duration, and seasonal timing of baseflows, spring/summer runoff, and winter floods	Inundation of bar features during dispersion of riparian plant seeds discourages germination on bars Variable water depths and velocities over spawning gravels during salmonid spawning spatially distributes redds Inundation of alternate bar margins, including backwater scour channels, creates shallow slackwater areas between late-winter and snowmelt periods for early life stages of salmonids and amphibians Provides favorable ranges of baseflows for maintaining high quality juvenile salmonid rearing and macroinvertebrate habitat within an alternate bar morphology Provides late-spring outmigrant stimulus flows In general, optimizes salmonid physical habitat availability for all seasons In general, restores groundwater/surface water dynamics and maintains hyporheic habitats In general, restores floodplain/riparian processes associated with a snowmelt hydrograph
Frequently mobilized channelbed surface	Coarse sediment surfaces are mobilized by the bankfull discharge, which on average occurs every 1 to 2 years	Reduced substrate embeddedness in riffle/run habitats increases survival of eggs and emerging alevins Scouring and reduced sand storage in pools creates greater pool depths/volumes for adult fish cover and holding Provides turnover of spawning gravel deposits and mobilizes those deposits several layers deep Provides greater substrate complexity in riffle and run habitats for improved macroinvertebrate production Decreases riparian encroachment by scouring seedlings on bars In general, increases micro-habitat complexity

Table 5-1. Alluvial River Attributes [1/], continued

Periodic channelbed scour and fill	Channelbed and bars are scoured deeper than the coarse surface layer by floods exceeding 3- to 5-year annual maximum flood recurrences	Scouring below bed surface layer rejuvenates spawning gravel deposits Facilitates bar evolution (e.g., alternate, medial), improving channel-wide spawning and rearing habitat complexity Maintains and/or improves pool depths for adult salmonid cover and holding Increases diversity of surface particle size distributions Removes vegetation from bar surfaces, discouraging riparian plant encroachment and bank accretion Deposits fine sediment onto upper alternate bar and floodplain surfaces, thereby reestablishing dynamic riparian stands of vegetation in various stages of succession
Periodic channel migration	"Typical" bank erosion rates, floodplain deposition every 3 to 5 years, and channel avulsions every 10 years on average	Diverse age class structure of woody riparian vegetation, producing and maintaining early- successional riparian communities Increase in woody riparian overstory and understory species diversity Increased habitat quality and quantity for native vertebrate species dependent on early successional riparian stands High flow refuge and summer thermal refuge for amphibians and juvenile fish provided in rejuvenated scour channels Salmonid habitat complexity is improved through creation of sloughs and side channels Increasing micro-habitat complexity from input of large woody debris caused by bank erosion
Balanced fine and coarse sediment budgets	Fine and coarse sediments are exported at rates approximately equal to sediment inputs. Channel morphology is maintained in "dynamic quasi-equilibrium"	Reduced fine sediment storage and maintained coarse sediment storage improves spawning habitat quality without reducing quantity Mobilization of coarse sediments and preventing mainstem accumulation of fine sediments increases pool depths for adult salmonid cover and holding, and improves physical complexity through bar evolution Reduced fine sediment storage in banks lessens bank accretion, thereby allowing continual evolution of channel morphology Discouraging bed elevation aggradation at tributary deltas maintains salmonid migration corridors
Functional floodplain	Areas where fine sediments can be removed from the inner channel and deposited	Through scour and deposition, floodplain construction rates roughly equal floodplain loss as channel migrates Provides sufficient channel confinement, such that hydraulic processes can be maintained Increases hydraulic roughness, and allows greater flow storage during high magnitude floods Maintains riparian vegetation dynamics, such as varying stages of successional development

Table 5-1. Alluvial River Attributes [1/], continued

Infrequent channel resetting floods	Those that exceed the 10- to 20-year annual maximum flood recurrence	Salmonid habitat complexity and quantity is improved through deep scour of channel features, significant channel migration and avulsion (creating sloughs and side channels), and alternate bar scour and redeposition Maintain riparian vegetation dynamics, such as varying stages of successional development Disturbs bar surfaces close to channel center to discourage riparian encroachment Provide habitat for riparian-dependent amphibian, avian, and mammalian species Improves bedload routing by minimizing impedance of bedload transport past tributary deltas
Self-sustaining diverse riparian plant communities	Successional stages and species composition similar to other regional unregulated river corridors	Increase in species diversity, and age class diversity Increase in riparian habitat complexity Allows rehabilitation of evolving channel features (e.g., alternate bars, sloughs) Vigorous woody riparian corridor moderates physical effects of extreme floods Increases availability of habitat for riparian-dependent amphibian, avian, and mammalian species Moderates water temperatures at the micro- habitat scale
Interstitial flow pathways and ground water/surface water interactions	Hyporheic habitats form because of interstitial pathways between surface water and groundwater. Hydrology of floodplains, terraces, sloughs, and adjacent wetlands fluctuate in response to natural hydrograph of river corridor	Maintains off-channel habitats, including overflow channels, oxbow channels, and floodplain wetlands Promotes diversity of habitat types within entire river corridor Farms and maintains hyporheic habitats, which diversify salmonid spawning and rearing habitat (e.g., increased interstitial flow through redds, temperature refugia, water quality control, etc.)

1/ Compiled from several sources, primarily the Trinity River Restoration Program (Hoopa Valley Tribe, 1997).

The post-impoundment functioning of the lower Snake River could be regarded as more ecologically sustainable, as the functional and structural characteristics come closer to the alluvial river attributes described in Table 5-1. The rate and pathways for recovering these attributes in the lower Snake River depend on many interrelated factors, one of which is the physical template set by the river prior to impoundment (the pre-dam channel morphology described in this study). Other factors, yet to be addressed or resolved, governing the recovery of lower Snake River physical processes and characteristics include:

- Post-impoundment management of the lower Snake River flow regime (magnitude, timing, duration, and frequency of base flows, bankfull flows, riparian flows, and floodplain flows)
- Quantitative sediment budgets for the Snake River and its tributaries

- Quantitative assessments of existing substrate composition in the lower Snake River
- Quantitative assessments (e.g., spatial extent, composition, effects) of existing riprap along banks
- Quantitative assessments (e.g., spatial extent, composition, effects) of proposed shoreline protection, velocity control structures (e.g., riprap, levees) and other channel alterations following dam breaching
- Quantitative assessments (e.g., spatial extent, composition, effects) of river channel alterations occurring between 1934 and completion of the first lower Snake River dam (1961), and from 1961 to present-day (e.g., channel/reservoir maintenance, dredging, in-channel disposal)
- Quantitative assessments of the hydraulic and geomorphic effects upriver, at the dam, and downriver resulting from the dam structures remaining in place (e.g., navigation lock, spillway, powerhouse) after dam breaching

These and other factors determine the rate and means by which the lower Snake River will evolve from its present condition to that described by the pre-dam channel morphology. A prediction of the precise style and rate of this channel adjustment is precluded by the nonexistence of quantitative process-response models of channel adjustment (Richards, 1982; Hooke, 1997). The interdependence of the nine or more variables defining and controlling stable channel geometry (Hey, 1997), which respond differently to changes in sediment quantity and composition and flow regime, confounds even qualitative predictions of channel adjustment (Hooke, 1997). Moreover, these changes in sediment yield and flow regime are naturally altered simultaneously but to different and variable degrees, often with secondary responses (Richards, 1982). The magnitude and direction of channel change in response to changes in sediment yield and flow regime can be addressed qualitatively through relationships originally proposed by Schumm (1969). The nature of the channel response for any given segment of the lower Snake River depends on the inherent instability, the freedom to adjust (vertically and laterally), and the sensitivity of different environments and reaches to change (Hooke, 1997). The classification of the lower Snake River into distinct geomorphic units—the template controlling stability and sensitivity—provides a framework for developing hypotheses of possible channel responses.

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Part 2

Two-dimensional Analysis of Hydraulic Conditions and Sediment Mobility in the Lower Snake River for Impounded and Unimpounded River Conditions

6. Summary

The lower Snake River hydrograph is affected by water and land management practices throughout the watershed, and controlled by upstream dam releases, consequently, it is certain that the river channel will not be restored to its pristine pre-development condition by removing the four lower Snake River dams. Exactly how the resultant channel bed would differ from the original channel is uncertain, although this study does provide a comparative analysis of impounded and unimpounded river conditions.

The objective of the study was to compare hydraulics and sediment mobility in the lower Snake River for current and unimpounded river conditions using a mathematical model of the river and water quality model. The analysis used three steady flow conditions corresponding to the discharged exceeded 10, 50, and 80 percent of the time (based on historical flows).

The results of the hydraulic simulations showed that, for the 50 percent exceedance flow (31,710 cfs), the unimpounded river conditions are characterized by a wider range of depth-average velocities. For impounded conditions, the majority of river area had velocities less than 2 feet per second. In comparison, the unimpounded river condition shows that most of the velocities are in the range of 1 to 8 feet per second. The unimpounded conditions case also shows that velocities will be more evenly distributed over that range.

Based on critical velocity criteria, simulations for the 50 percent exceedance flow for impounded conditions showed that mainly sediments finer than a medium sand (0.25 mm diameter) would be mobilized or remain in transport. In the unimpounded river case, the same flow would mobilize medium (16 mm) to coarse gravel (64 mm) or finer material over most of the river channel. Thus, for typical flow conditions, most of the fine sediments that have been deposited in the lower Snake River reservoirs will be remobilized and transported downstream. The dominance of coarse material is consistent with current observations of substrate composition in the areas immediately downstream of the dams.

Recent research on gravel-bedded streams indicates that the bed shear stress may have to be three times higher to initiate movement in a substrate composed of coarse materials interlaced with fine sediments, as compared to the uniform bed criteria. The potential decreased mobility of the coarse materials (larger than fine gravel) was examined using a velocity criteria 1.5 times higher than the uniform criteria. Under those conditions, 10 percent exceedance flows (111,500 cfs) may be required to mobilize the same area of coarse materials, as was the case using the uniform criteria at the 50 percent (31,170 cfs) exceedance flow.

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7. Introduction

The goals of this analysis are to provide an improved understanding of the differences in hydraulic regimes between the current (impounded) and "natural" (unimpounded) conditions, as well as to estimate sediment mobility for each condition. This is accomplished using a two-dimensional (2D), depth-averaged, hydrodynamic model to simulate the velocity distribution in the river. Estimates of the size of sediment that can be mobilized are then developed using the simulated velocities, along with sediment movement criteria based on critical velocity or shear stress.

7.1 Geographic Scope

In this work, the term "lower Snake River" refers to the area of the Snake River where the model was applied. This analysis area goes from the mouth of the Snake River (river mile 0), at the confluence with the Columbia River, to Snake River mile 168, near its confluence with the Grande Ronde River. A small reach of the Clearwater River (about 1 mile) is also included. This geographic scope is shown in Figure 7-1.

7.2 Key Assumptions and Limitations

The analysis presented in this report contains several assumptions and limitations:

- The long-term (after dam breaching) future channel course and bathymetry is represented by historical pre-dam bathymetric surveys;
- Sediment mobility or transport potential is described by critical velocities;
- Steady-state flows are adequate to perform a comparative analysis; and
- The evolution of the channel bed is not simulated.

Assuming that the long-term channel configuration is represented by pre-dam bathymetry is reasonable considering that the lower Snake River was primarily a non-alluvial system characterized by armored cobble/gravel bed materials and areas of bedrock. If the dams are breached, the river will cut through existing fine material that has been deposited, and the floodplain will widen to its former limits with successive high flows as remaining fine sediments are eroded. At small scales, there will obviously be differences between the channel that existed prior to dam closure and that which would form 5 to 10 years after dam breaching. For the present purpose of characterizing the differences in hydraulic conditions at a large scale, performing the analysis based on historical bathymetry is adequate.

The primary reason for not simulating the evolution of the channel bed, beginning from dam breaching to some future stable state, is the lack of available data, along with the uncertainty of sediment transport modeling in general. Such a modeling effort will require field surveys to characterize the existing channel bed elevation, estimated depth of sediment, bed sediment grain size distribution, and incoming sediment loads (some older data are available in Jones and Seitz 1980). Some of this data exists for Lower Granite Lake (Figure 7-2) but, even there, it is sparse and biased to nearshore locations or towards finer sediment sizes. In addition to inriver sediment transport processes, the erosion and overland transport of material along the exposed shore that will appear when the water level drops should be accounted for in any modeling effort. The rate and extent of revegetation should also be considered. Without additional data, bed evolution simulation would, at best, be highly speculative at the present time.

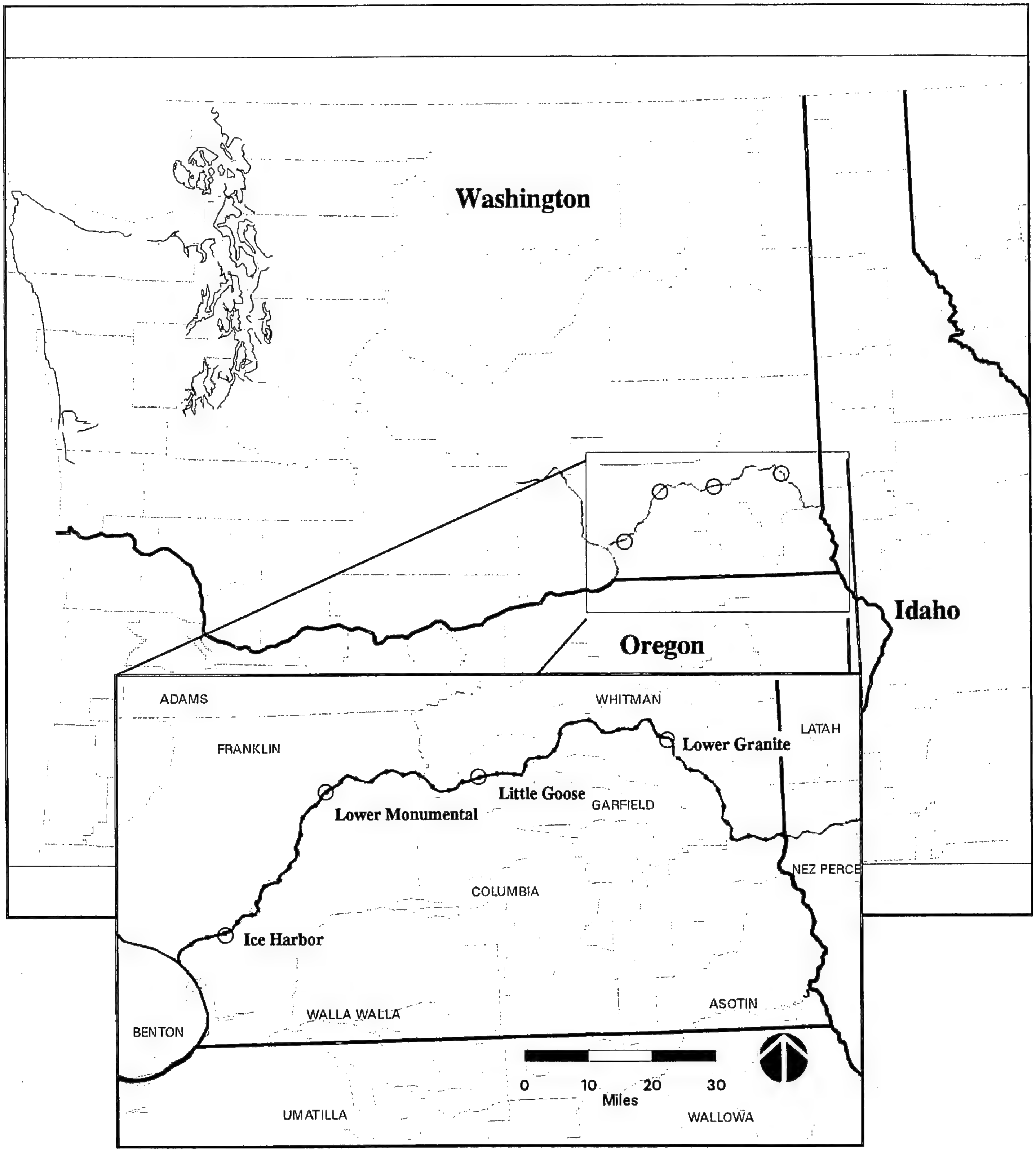
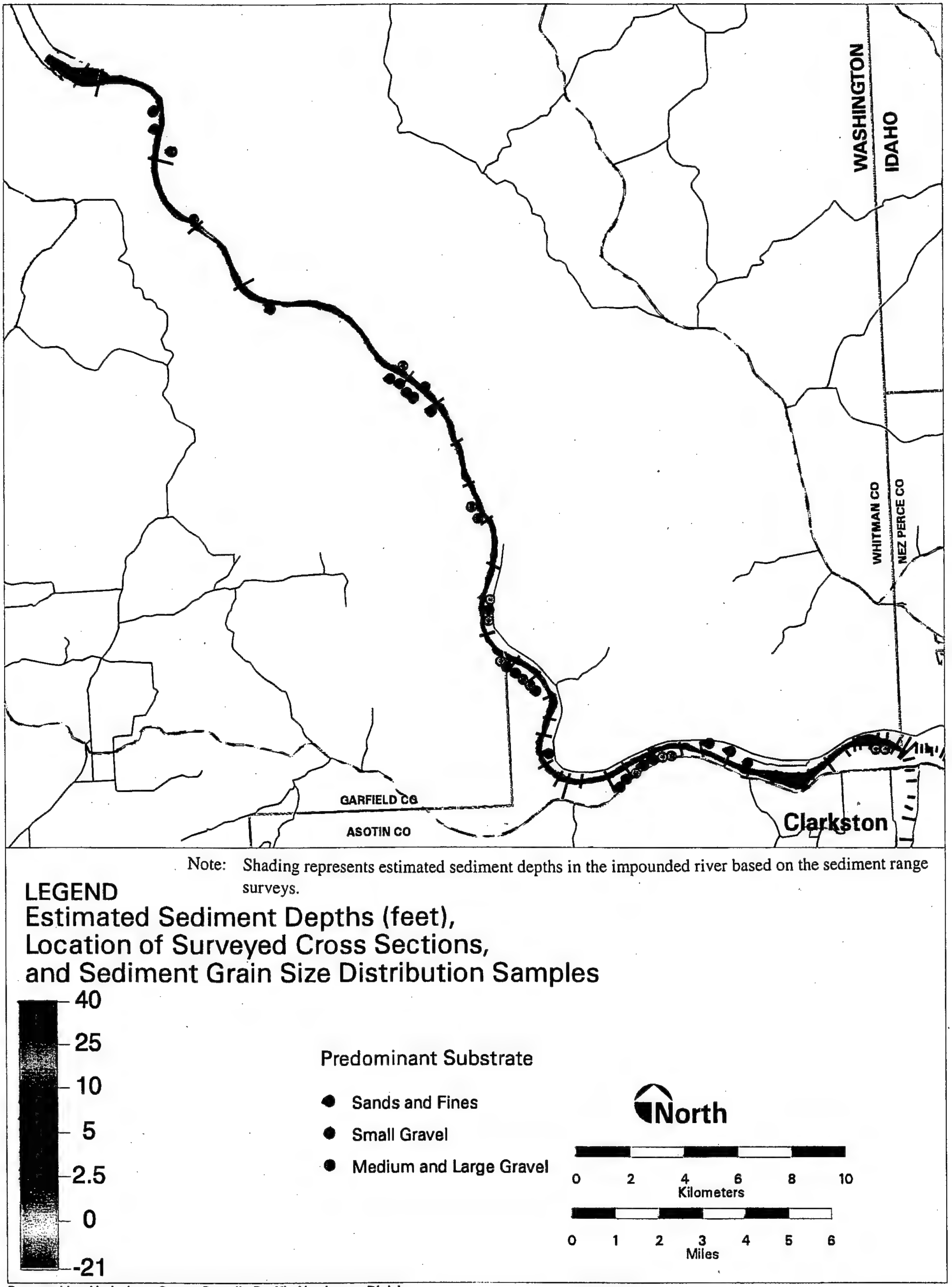


Figure 7-1. Reach of the Lower Snake River Where the 2D Model Was Applied in This Analysis



Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: May 20, 1999

Figure 7-2. Location of Surveyed Sediment Ranges and Grain Size Distribution Samples

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8. Methods

The analysis of hydraulic conditions for both impounded and unimpounded river conditions uses a two-dimensional (2D), depth-averaged, hydrodynamic model. This section presents the essential aspects of the numerical model, bathymetric data, boundary conditions, and parameters.

8.1 2D Model

The 2D model used in this analysis is the Modular Aquatic Simulation System 2D (MASS2), developed for the Dissolved Gas Abatement Study (DGAS) for the Corps (Richmond at al., 1998). This model was selected because it has been configured and applied to the lower Snake River analysis area for impounded conditions. Applying the model for natural river conditions only required setting up new computational grids, as described below.

The MASS2 model simulates unsteady hydrodynamics (flow) and transport for 2D depth-averaged conditions. The MASS2 is a finite-volume code that uses a structured multi-block, curvilinear grid system. The 2D model numerically solves the governing equations of mass and momentum conservation to yield values of the water surface elevations, velocity, temperature, and total dissolved gas (not used in the Feasibility Study). These values are produced at each grid cell for every time step in the simulation. Output results can be captured as time-series data, a specific grid cell, or as spatial snapshots over the entire simulation domain for a certain time. The spatial results can be imported into GIS software for further analysis and map production. A complete description of the model and its application to the lower Columbia and Snake Rivers is provided by Richmond et al. (1998).

8.2 River Bathymetry and Computational Grids

A 2D depth-averaged model, such as MASS2, represents the river as a system of cells in a computational grid. This grid is constructed using geographic information describing the river shoreline and bathymetry (bottom elevation). The specific procedures for generating the computational grids for MASS2 are described in the DGAS summary report (Richmond et al., 1998).

Grids for the impounded conditions were the same as those used in the DGAS study. The bathymetry data used in those grids are based on present-day measurements, which are adequate for 2D modeling for full-pool conditions. These bathymetric data are too coarse (unless subjected to an excessive degree of smoothing) for 2D modeling, except for Lower Granite Lake and areas within about 1 mile of the downstream dams. An example of a grid for impounded conditions is shown in Figure 8-1.

Bathymetry and shoreline data for the natural river grids are based on electronically-digitized versions of the so-called 1934 linens (Corps, 1934). This data has sufficient resolution to use in a 2D model. These data are also consistent with the objective of simulating representative hydraulic conditions that would be present several years after a return to natural river conditions. Two grids were developed using the 1934 data: one for use in the 10 percent exceedance case and one for the 50 percent and 80 percent exceedance cases. Figure 8-2 is an example of the grid for the 50 percent exceedance case.

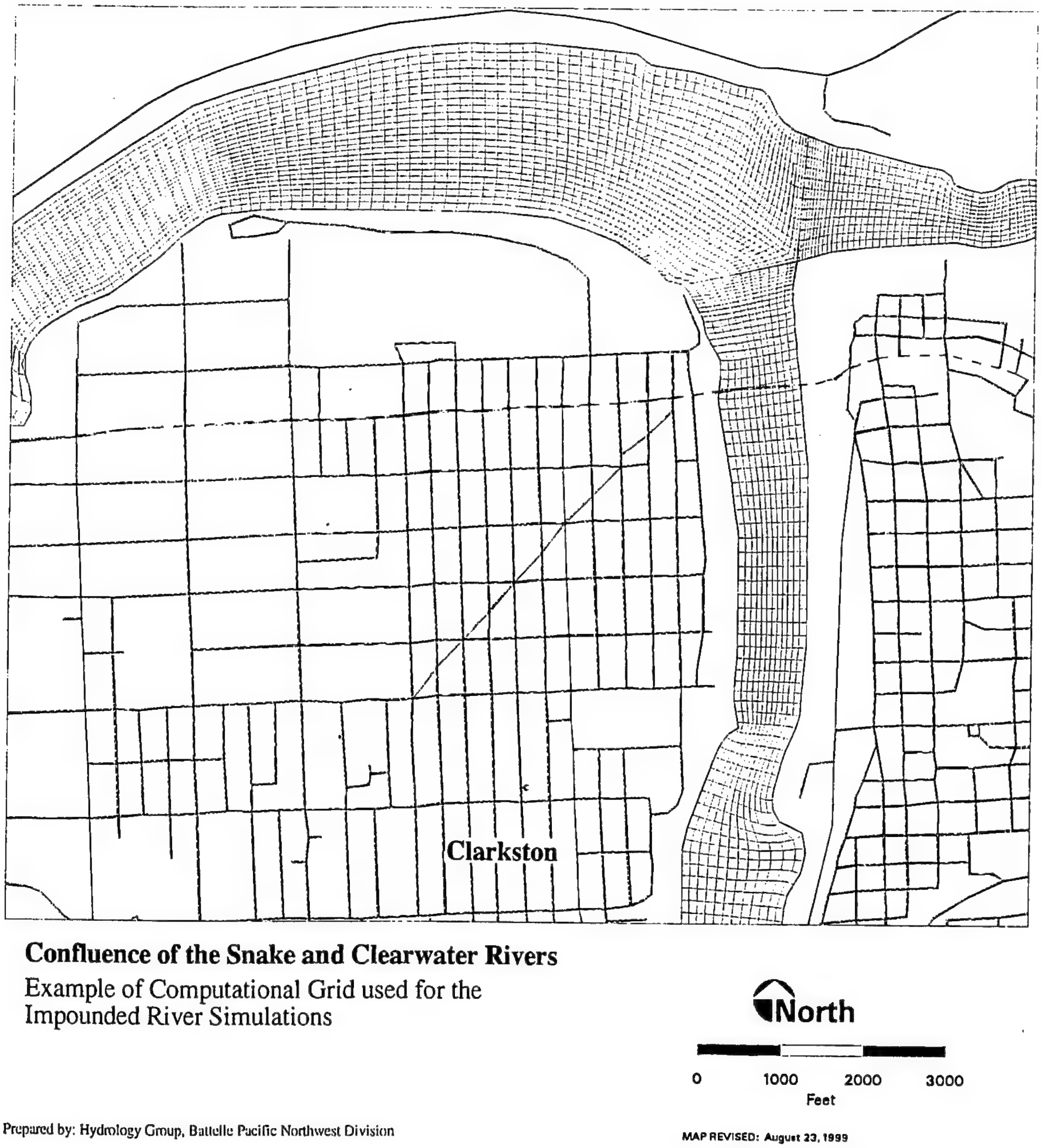
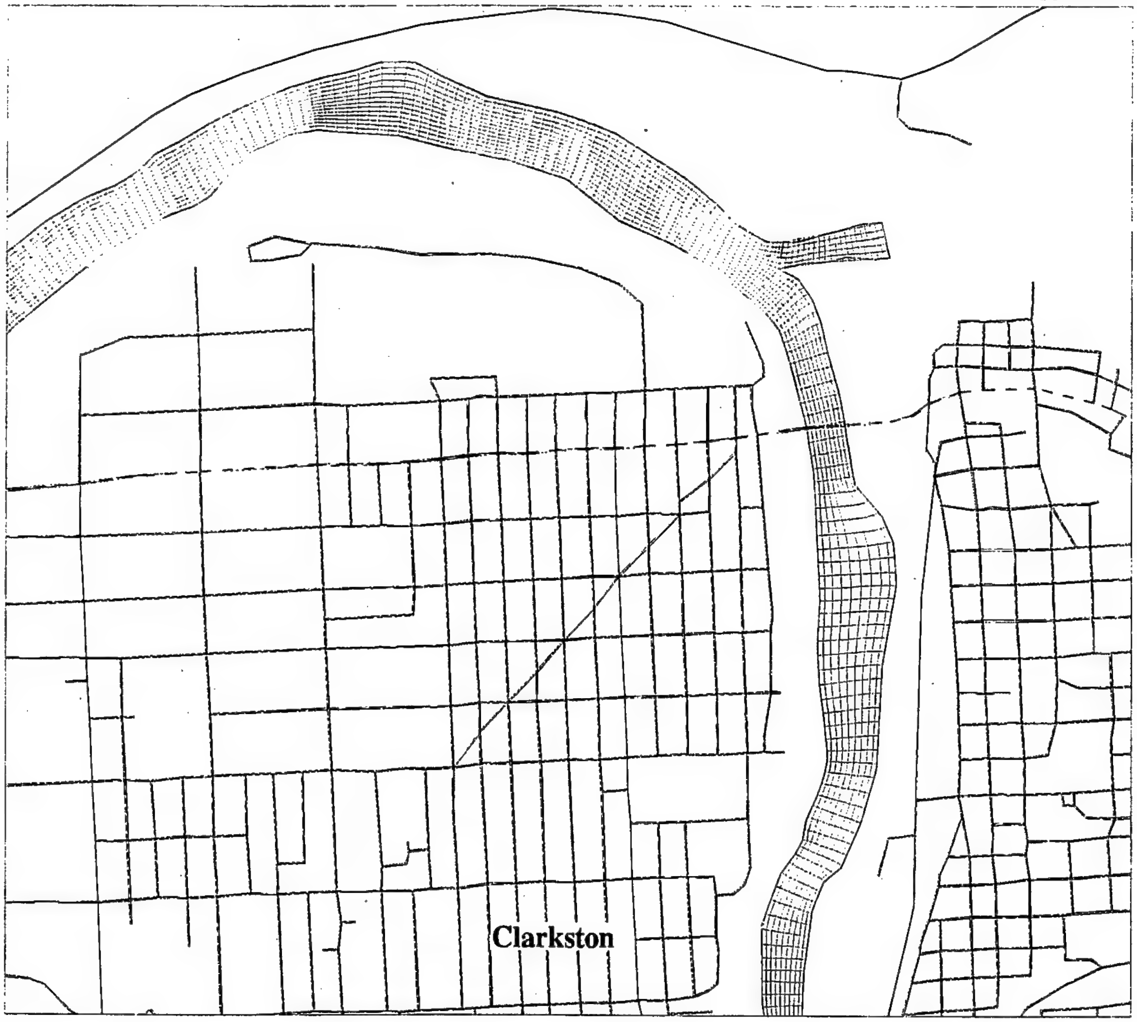


Figure 8-1. Example of the Computational Grid Used in the Full-pool, Impounded Conditions Simulations

8.3 Model Boundary Conditions and Parameters

The model was run for three steady-flow conditions corresponding to the 10 percent, 50 percent, and 80 percent exceedance flows for impounded conditions and natural river conditions. These exceedance flows were calculated in Hanrahan et al. (1998). The exceedance or flow duration is shown in Figure 8-3, and selected values are given in Table 8-1. The total flow at Lower Granite Dam was split between the Snake and Clearwater Rivers to assign model inflows, using fractions of 2/3 and 1/3, respectively.



Confluence of the Snake and Clearwater Rivers

Example of Computational Grid used for the Unimpounded River Simulations

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure 8-2. Example of the Computational Grid Used in the Unimpounded River Conditions Simulations

Inflows from other tributary streams (i.e., the Palouse and Tucannon) were not included in these simulations, because they are less than 2 percent of the Snake River flow at Lower Granite Dam.

Simulations for impounded conditions used steady-state forebay elevations corresponding to the normal operating pool elevation for each reservoir. For both the impounded and natural river simulations, a water surface elevation was specified at the confluence of the Snake and Columbia rivers. These various elevation boundary conditions are summarized in Table 8-2.

Manning roughness coefficients of 0.024 and 0.028 were used in the impounded and unimpounded river condition simulations, respectively.

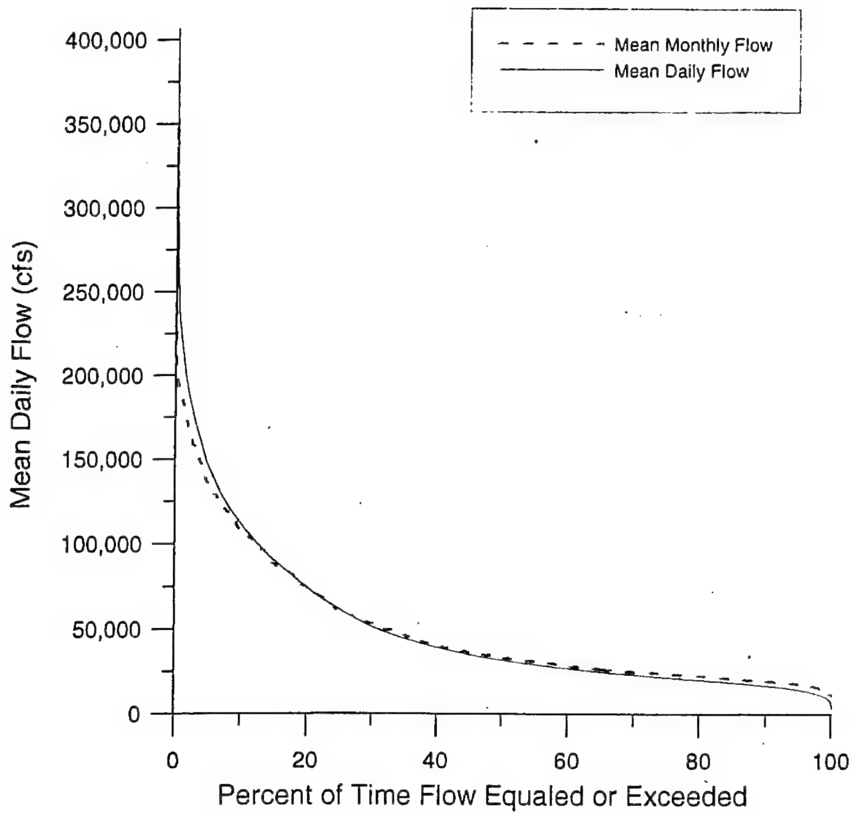


Figure 8-3. Flow Duration Curves Based on Mean Monthly and Mean Annual Flows at Lower Granite Dam

Table 8-1. Lower Granite Flow Exceedances

Percent of Time Equaled or Exceeded	Discharge (cfs)
10	111,500
20	74,260
50	31,710
80	19,900
90	16,680

Table 8-2. Elevation Boundary Conditions Used in the Simulations

Boundary	Elevation
Lower Granite Dam	738 feet
Little Goose Dam	635 feet
Lower Monumental Dam	540 feet
Ice Harbor Dam	440 feet
Columbia-Snake River Confluence	341 feet

8.4 Criteria for Initiation of Sediment Movement

The sediment mobility criteria are based on American Society of Civil Engineers (ASCE, 1975) standards, and provide an estimate of the mean velocity and bed shear stress required to initiate movement. Table 8-3 lists the critical values of velocity and bed shear stress for each sediment size class. The velocity criteria are based on the classical Hjulstrom curve. The shear stress criteria are based on the Shields curve, which does not apply to cohesive sediments (less than 0.0625 millimeters). Site-specific tests are usually required to estimate the critical shear stress for cohesive sediments.

Table 8-3. Sediment Size Classification and Criteria for Initial Movement

Class Name	Size (mm)	Critical Erosion Velocity (ft/sec)	Critical Shear Stress (lb/ft^2)
Boulders	256.0000	12.0	5.20000
Cobbles	64.00000	9.0	1.30000
Very Coarse Gravel	32.00000	7.3	0.62000
Coarse Gravel	16.00000	5.0	0.32000
Medium Gravel	8.00000	3.2	0.16000
Fine Gravel	4.00000	2.0	0.07000
Very Fine Gravel	2.00000	1.3	0.02950
Very Coarse Sand	1.00000	0.8	0.01230
Coarse Sand	0.50000	0.7	0.00540
Medium Sand	0.25000	0.6	0.00364
Fine Sand	0.12500	0.7	0.00306
Very Fine Sand	0.06250	0.8	0.00257
Coarse Silt	0.03100	1.1	
Medium Silt	0.01600	1.6	
Fine Silt	0.00800	2.2	
Very Fine Silt	0.00400	3.5	
Coarse Clay	0.00200	5.5	
Medium Clay	0.00100	8.0	
Fine Clay	0.00050	11.0	
Very Fine Clay	0.00024	14.0	
Colloids			

It should be noted that these criteria are not exact, and there is uncertainty with regard to the precise hydraulic conditions that initiate sediment movement, however, these criteria are used to indicate the representative conditions that will generally lead to the erosion of bed material of a given size class. The results in Section 9 are presented in terms of the critical velocities, since grain size distribution data are not available to modify the Shields criteria for non-uniform bed material.

8.5 Habitat Suitability Criteria for Spawning Fall Chinook Salmon

Areas of potentially suitable habitat for spawning fall chinook were determined by applying criteria for preferred spawning habitat to the hydrodynamic conditions simulated in model runs for impounded and unimpounded river conditions for the 50 percent exceedance flow (31,710 cfs). The criteria were the same as those used in a study by the U.S. Fish and Wildlife Service (USFWS) in 1999. For spawning chinook, suitable habitats had: 1) depth-averaged velocities between 1.3 and

6.4 feet per second; 2) depths between 1.3 and 21 feet; and 3) substrates categorized as gravel, cobble, gravel/cobble, cobble/gravel, and cobble/sand.

Point data from MASS2 simulations, including depth and depth-averaged velocity, were intersected with substrate data derived from pre-dam maps (Corps, 1934). The suitability criteria were applied to each point, and coded as "suitable" if all three criteria were met, and "unknown" if substrate data were not available at that point, but velocity and depth criteria were satisfied. All other points were classified as "unsuitable." These irregularly-spaced classified point data were then converted into a regularly-spaced, 40-foot grid, using ArcInfo. Statistics from this grid were used to calculate the area and potential suitability of spawning habitat for the 50 percent exceedance flow (31,710 cfs) for both the impounded and unimpounded river.

8.6 Habitat Suitability Criteria for Juvenile Fall Chinook Salmon

Areas of potential suitable habitat for spawning fall chinook were determined by applying criteria for preferred spawning habitat to the hydrodynamic conditions simulated in model runs for impounded and unimpounded river conditions for the 50 percent exceedance flow (31,710 cfs). The criteria were the same as those use in a study by USFWS in 1999. For juvenile fall chinook, suitable habitats had: 1) mean velocities less than 4 feet per second; 2) depths between 0.3 and 5.3 feet; and 3) were located within 81.7 feet of the shore.

ArcInfo was used to determine the areas within 81.7 feet of the shore, and those data intersect with MASS2 simulation point data for the 50 percent exceedance flow. The suitability criteria was applied to each point, and the point coded as "suitable" if all three criteria were met. Otherwise, they were classified as "unsuitable." The irregularly-spaced classified point data were then converted into a regularly spaced 40-foot ArcInfo grid. Statistics from this grid were used to calculate the area and suitability of potential rearing habitat for the 50 percent exceedance flow (31,710 cfs) for both the impounded and unimpounded river.

9. Results

The velocities and depths computed by the MASS2 model were used to compare the hydraulic and sediment mobility characteristics for impounded and unimpounded river conditions. Examples of figures showing spatial distributions for velocity, substrate particle size, and habitat at 10, 50, and 80 percent exceedance flows are presented in Annexes A, B, and C. The full set of figures for the entire lower Snake River can be viewed electronically on the Walla Walla District home page (http://www.nww.usace.army.mil).

9.1 Flow Conditions

Verification data for the model were not available for the unimpounded river cases. The MASS2 model has been extensively verified for current impounded conditions (Richmond et al., 1998). Figures 9-1 and 9-2 show comparisons between simulated and measured velocities in the area downstream of Lower Granite Dam. Although these are not strictly unimpounded river conditions, these results do show that the model is able to adequately represent velocities in shallow areas for current conditions.

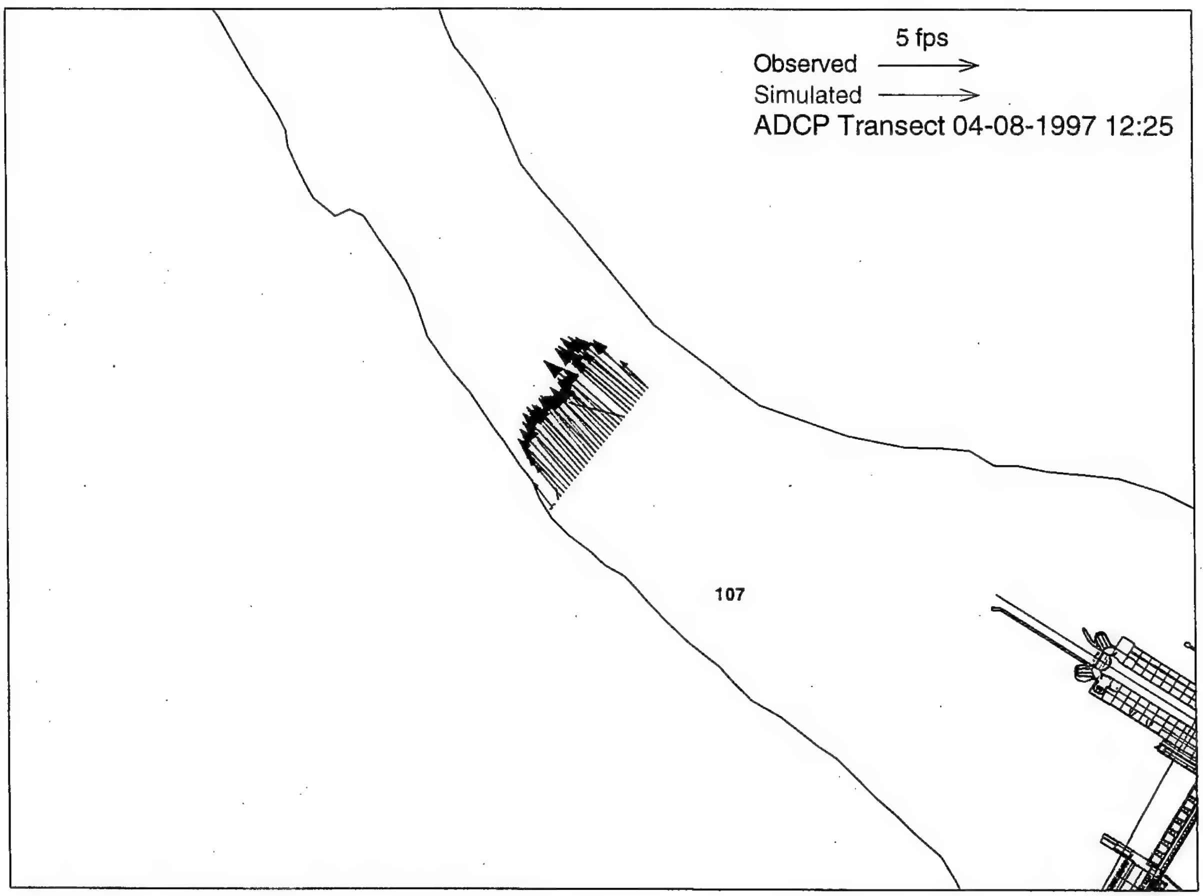


Figure 9-1. Comparison of Simulated and Measured Depth-averaged Velocities Near Snake River Mile 107 (downstream of Lower Granite Dam) for Impounded Conditions

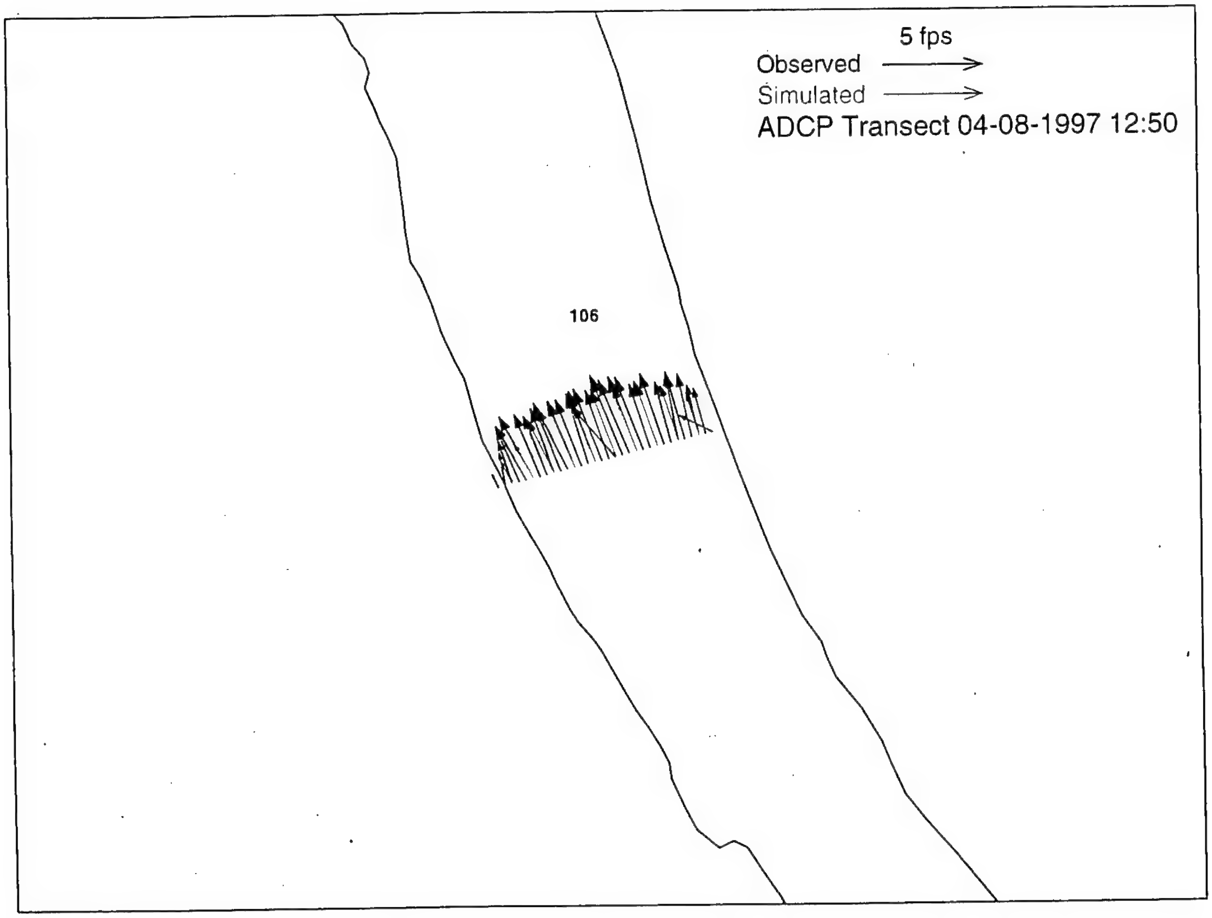


Figure 9-2. Comparison of Simulated and Measured Depth-average Velocities Near Snake River Mile 106 (downstream of Lower Granite Dam) for Impounded Conditions

Tables 9-1 and 9-2 compare the river surface areas and velocities for the impounded and unimpounded river cases. The unimpounded river has higher velocities and a more variable distribution of velocities.

Table 9-1. Comparison of River Surface Areas for Impounded and Unimpounded River Conditions

Region	Impounded River (Acres)	Unimpounded 10 Percent (Acres)	Unimpounded 50 and 80 Percent (Acres)
Lower Granite	7,541	3,255	2,816
Little Goose	9,310	4,592	3,749
Lower Monumental	5,803	3,450	3,124
Ice Harbor	7,954	4,290	3,558
McNary	1,788	1,810	1,988
Total	**32,395**	**17,397**	**15,236**

Note: These areas were derived from vector-based polygons rather than the grid-based areas derived from model output. Therefore, they are slightly different than the total area in the velocity distribution comparison table.

Table 9-2. Comparison of Simulated Velocity Distributions for the 10, 50, and 80 Percent Exceedance-flows

Exceedance	10 Percent		50 Percent		80 Percent	
Velocity (ft/sec)	Impounded (acres)	Unimpounded (acres)	Impounded (acres)	Unimpounded (acres)	Impounded (acres)	Impounded (acres)
0-0.5	9,839	176	26,210	711	31,012	1,670
0.5-1	7,936	173	4,633	1,050	1,472	1,171
1-2	8,483	463	1,656	1,625	135	2,855
2-3	3,498	942	120	2,649	0	3,608
3-4	1,681	938	0	3,424	0	2,855
4-5	829	1,496	0	2,707	0	1,607
5-6	235	2,558	0	1,632	0	835
6-7	118	3,592	0	837	0	413
7-8	0	3,497	0	405	0	171
8-9	0	2,224	0	161	0	71
9-10	0	900	0	61	0	24
10+	0	460	0	45	0	11
Total Area	32,619	17,419	32,620	15,309	32,620	15,309

Note: 111,500, 31,710, and 19,900 cfs, respectively, of the Impounded and Unimpounded River Conditions

9.2 Sediment Transport

Surveyed sediment ranges in Lower Granite Lake, obtained from the Corps, were used to estimate the amount of sediment available for transport shown in Figure 9-3. Sediment transport rates were estimated using the Toffaletti methods (ASCE, 1975). The following output from the long-term model simulations were used in the Toffaletti method: average velocity, friction slope, and hydraulic radius. The method required the selection of a representative water temperature, median sediment size (D50), and settling velocity. A water temperature of 10°C (50°F), and a D50 of 0.5 millimeters (medium sand) were selected and used at each cross section. The transport rates computed from a medium sand will be smaller than those computed for a fine sand or silt. Therefore, the removal time estimates should be conservative in that a longer removal time will be computed for portions of the reservoir that have bed sediments composed of fine sands and silts.

An estimate of the time to remove the available sediment from Lower Granite Lake was calculated using the estimated available volume and transport rate. The sediment transport rate that was exceeded 50 percent of the time was used in these calculations. As shown in Figure 9-4, this estimate indicates that the time to remove the available sediment will be less than 5 years over the majority of Lower Granite Lake. This is in agreement with observations made during the 1992 drawdown test (Corps, 1993). Sediment transport rates measured during the drawdown test were comparable to the computed rates of about 44,000 tons per day at RM 137 (Figure 9-2). In addition, the drawdown test demonstrated that fine sediments were rapidly mobilized and transported, indicting the non-cohesive nature of post-impounded sediments. Note that the above removal time estimate for Lower Granite Lake applies only to the bankfull area of the river. Zones beyond the bankfull shoreline will require a longer time (less frequent flows) to return to pre-dam conditions. Wind and rain erosion and, where tributaries enter, channel incision processes will also affect these zones.

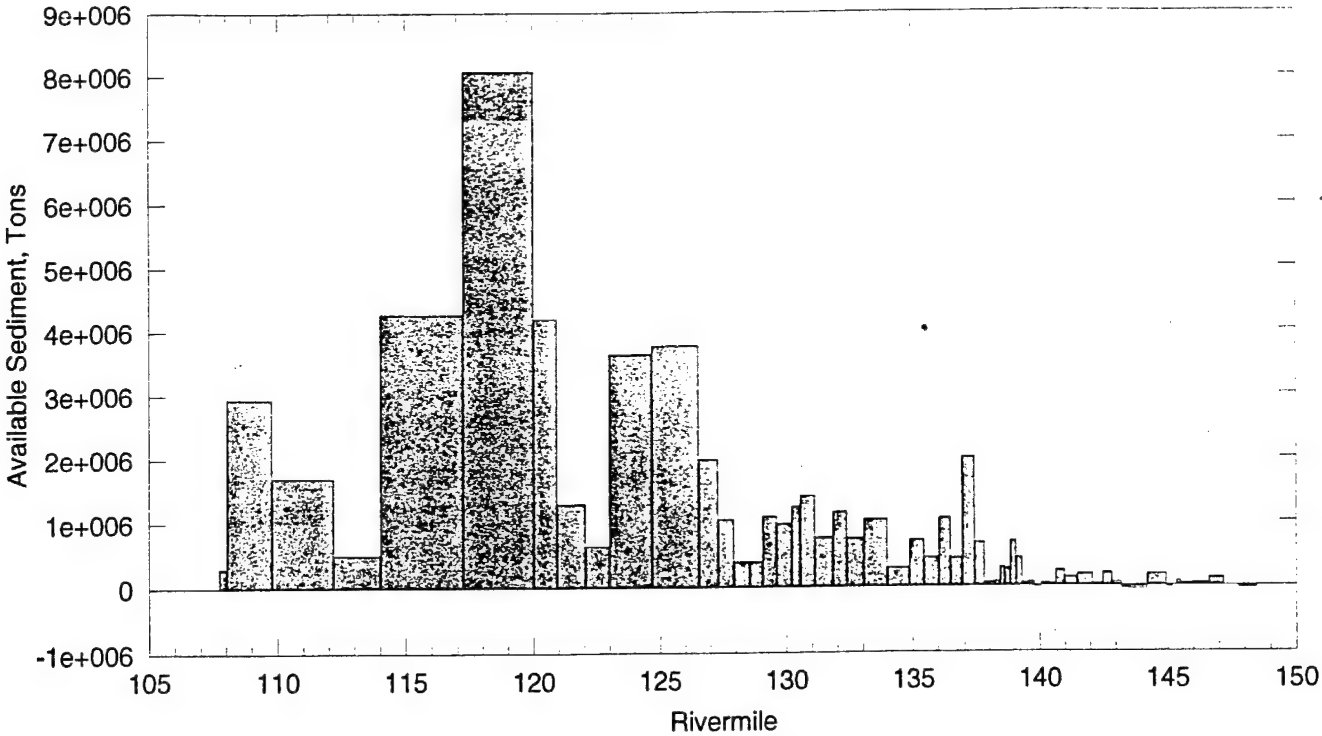


Figure 9-3. Estimated Available Sediment Along the Lower Granite Lake

Based on these calculations and the drawdown test field observations, the analysis compares current, impounded conditions to an unimpounded equilibrated condition 5 to 10 years after dam breaching. Again, the 1934 bathymetry is assumed to be representative of these future conditions.

Sediment mobility is estimated by using modeled velocities in conjunction with general criteria for the initiation of sediment movement presented in Section 9.4. Table 9-3 compares the estimated number of acres of river that would be capable of mobilizing different sized bed material. Except during high flows, impounded conditions are incapable of transporting significant amounts of material coarser than medium sand. The higher velocities in the dam-breaching alternative are able to mobilize material into the coarse gravel size range.

Recent work in gravel-bedded rivers suggests that these classic criteria for the initiation of sediment transport do not adequately represent field conditions. In some gravel-bedded rivers, the shear stress necessary to initiate motion is about twice the classic critical shear stress (Church et al., 1998), and the initial-motion shear stress can be up to three times the shear stress thresholds of final motion (Reid et al., 1985). Figures 9-5 and 9-6 show how the expected sediment in motion might change under a modified critical shear stress criteria that is 1.5 times the classic criteria for the 10 and 50 percent exceedance flow for materials coarser than fine gravels, respectively. As is demonstrated in these figures and Table 9-4, this modified criteria greatly reduced the area that would actively transport sediment larger than cobbles, although it would not change the area able to transport finer materials (including clays).

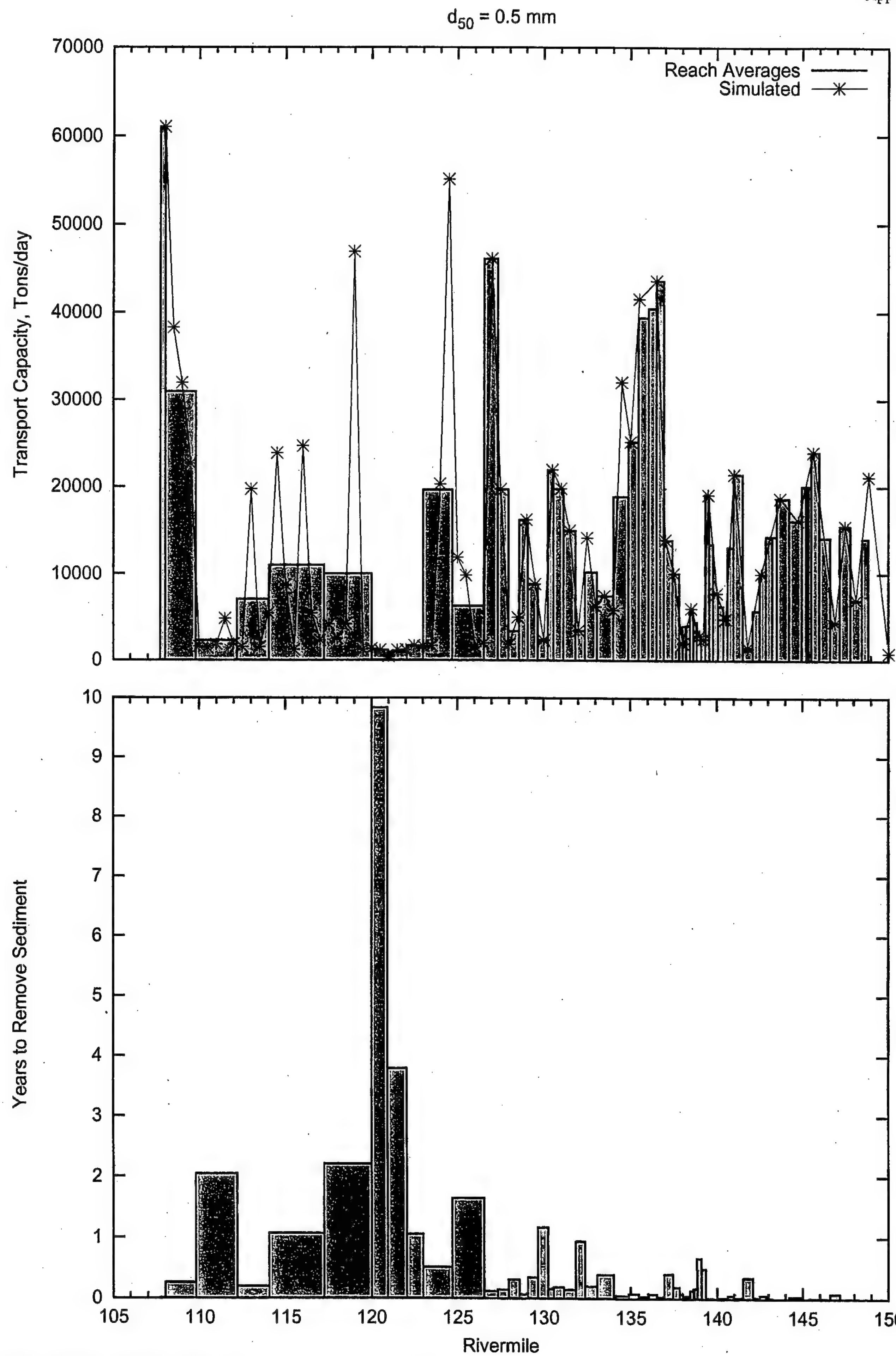


Figure 9-4. Estimates of Sediment Removal Time in Lower Granite Lake, Given a Sediment D50 of 0.5 Millimeters

Note: The upper graph shows simulated transport rates exceeded 50 percent of the time in Lower

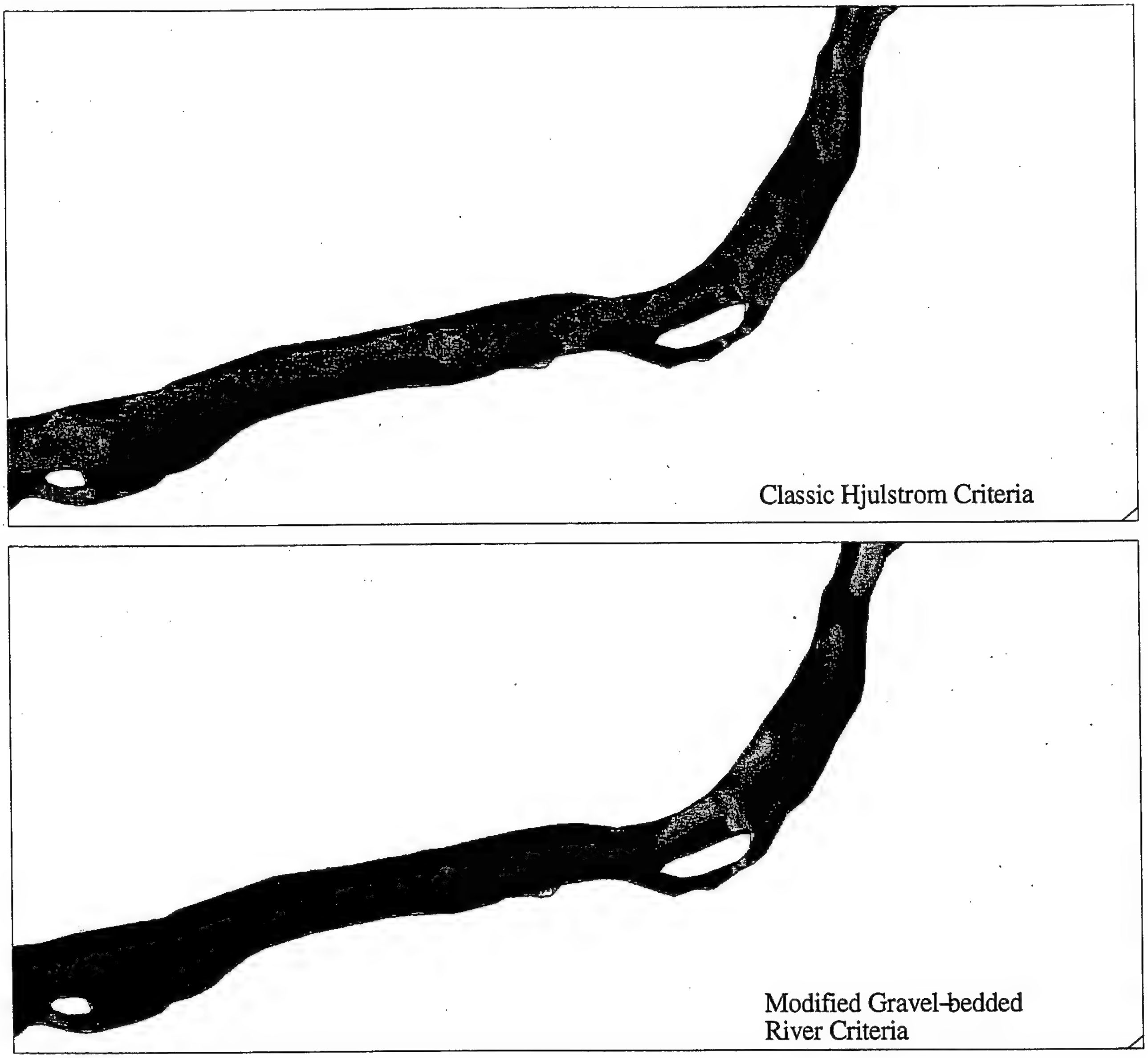
Table 9-3. Comparison of Sediment Mobility at the 10, 50, and 80 Percent Exceedance-flows (111,500, 31,710, and 19,900 cfs, Respectively) for the Impounded and Unimpounded River

Exceedance	10 Percent		50 Percent		80 Percent	
Sediment in Transport	Impounded (acres)	Unimpounded (acres)	Impounded (acres)	Unimpounded (acres)	Impounded (acres)	Unimpounded (acres)
Boulders	0	40	0	10	0	3
Cobbles	0	1,361	0	106		36
Coarse Gravels/Coarse Clay	354	13,230	0	3,360	0	1,667
Medium Gravel/Very Fine Silt	2,622	15,498	0	8,604	0	5,353
Fine Gravel/ Fine Silt	6,361	16,606	120	11,922	0	9,613
Medium Sand	21,056	17,209	4,795	14,396	959	13,352
Negligible Sediment Transport	11,564	210	27,825	913	31,661	1,956

9.3 Fall Chinook Habitat Suitability

Before addressing the results of the potential habitat suitability and availability analysis, it is critical to ascertain if the underlying data is of adequate resolution and quality to support such analyses. Bathymetric data for these studies were derived from the 1934 survey (Corps, 1934). These data consist of cross-sections of closely-spaced point data of 1/10th foot vertical resolution within the 1934 channel, and 5-foot contours outside the channel. Therefore, much better resolution of depth is expected for areas within the 1934 channel (i.e., the "unimpounded" river of this study) than outside the 1934 channel (i.e., between the shores of the current reservoirs and the unimpounded river), where the depth resolution is much coarser.

The spawning habitat criteria span a broad range of conditions that are met over large areas. The spawning habitat criteria require that depths are between 1.3 and 21 feet, with velocities between 1.3 and 6.4 feet per second. This range of depths is well resolved by the bathymetric data for impounded and unimpounded conditions, and the depth criteria are met over large spatial areas for both the impounded and unimpounded cases (24 and 94 percent of surface area, respectively). Sediment data were collected during pre-dam conditions, and little data exists for large spatial areas to determine changes in bed composition since the construction of the dams. Although the lower limit of velocity, 1.3 feet per second, is sufficient to mobilize and subsequently remove sand, it is not sufficient to mobilize finer materials such as medium silt or clays. Therefore, if sediment data is deemed representative of current conditions, the analysis should adequately represent potential spawning habitat availability for both the impounded and unimpounded conditions.



Ice Harbor Dam

Comparison of Criteria for Initiation of SedimentTransport for the 10 Percent Exceedance Flow 111500 cfs

Mobilized Substrate

- Cobbles (64mm)
- Very Coarse Gravel (32mm)
- Coarse Gravel (16mm)
- Medium Gravel (8mm)
- Very Fine Gravel and Coarse Sand (1-2 mm)
- Fine Sand (.125mm)

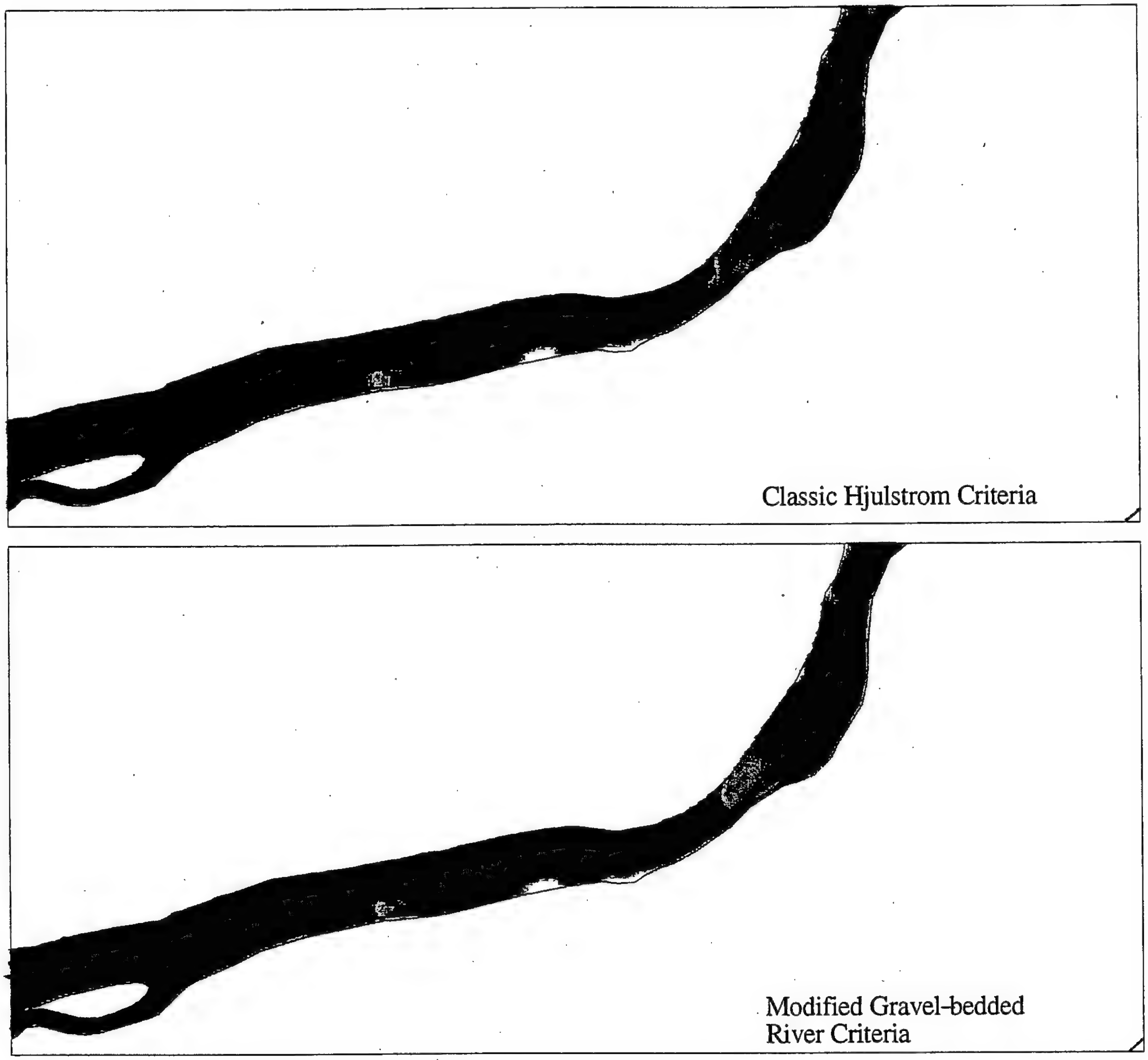
North

0 1000 2000 3000 4000
Feet

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure 9-5. Comparison of Mobilized Sediment for the 10 Percent Exceedance-flow Near Ice Harbor Dam for the Unimpounded River



Ice Harbor Dam

Comparison of Criteria for Initiation of SedimentTransport
for the 50 Percent Exceedance Flow 31710 cfs

Mobilized Substrate

- Cobbles (64mm)
- Very Coarse Gravel (32mm)
- Coarse Gravel (16mm)
- Medium Gravel (8mm)
- Very Fine Gravel and Coarse Sand (1-2 mm)
- Fine Sand (.125mm)

North

0 1000 2000 3000 4000
Feet

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure 9-6. Comparison of Mobilized Sediment for the 50 Percent Exceedance-flow Near Ice Harbor Dam for the Unimpounded River

Table 9-4. Comparison of Sediment Mobility Applying a Criteria More Appropriate for Gravel-bedded Rivers for the 10 and 50 Percent Exceedance-flows (111,500 and 31,710 cfs, Respectively) for the Impounded and Unimpounded River

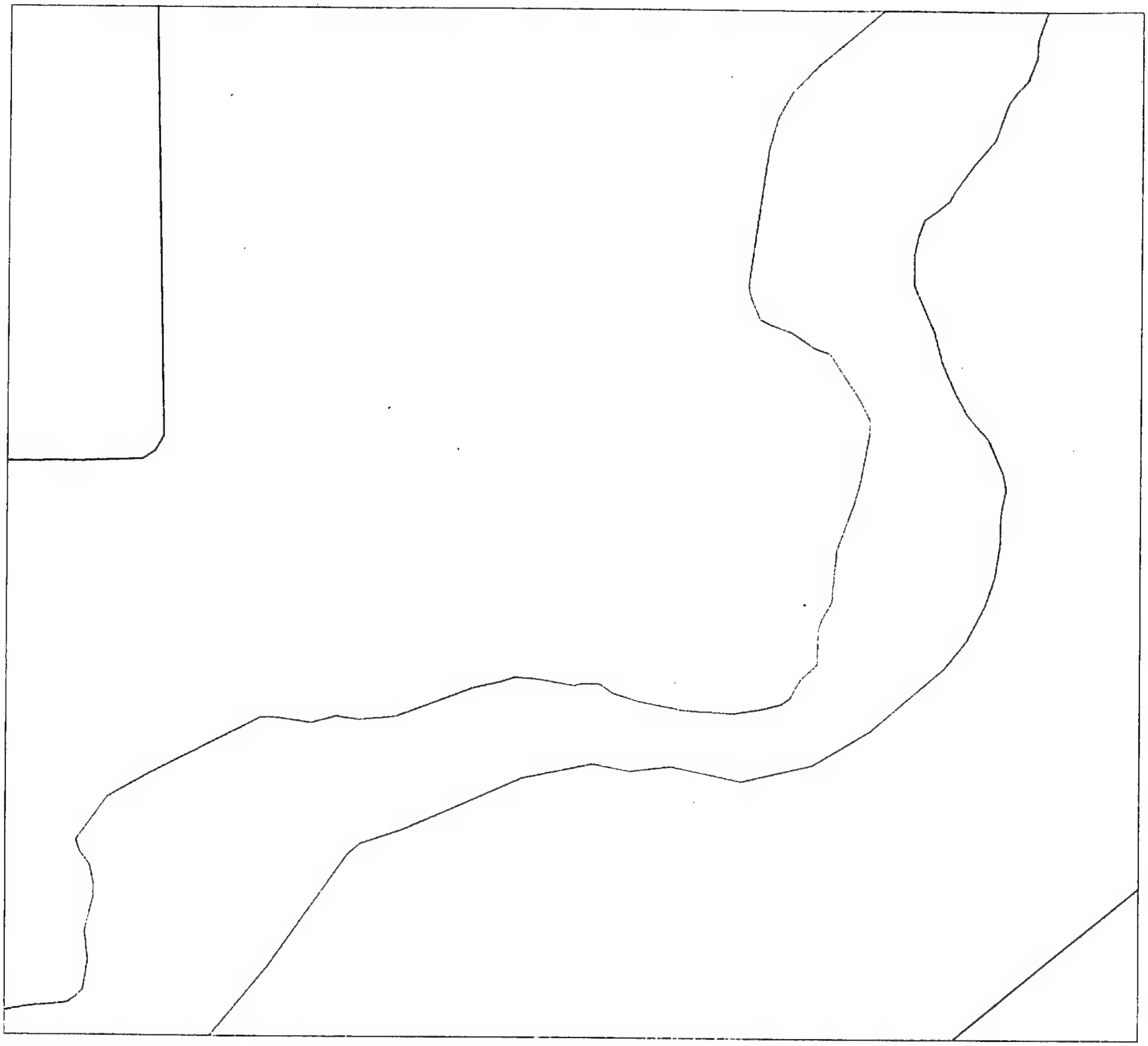
Exceedance	10 Percent		50 Percent	
Sediment in Transport	Impounded (acres)	Unimpounded (acres)	Impounded (acres)	Unimpounded (acres)
Boulders	0	0	0	0
Cobbles	0	8	0	4
Coarse Gravels	1	5,229	0	432
Medium Gravel/Clay	317	13,230	0	3,142
Fine Gravel/Very Fine Silt	1,880	15,236	0	7,545
Very Fine Gravel	6,154	16,727	120	11,922
Medium Sand	21,056	17,209	4,795	14,396
Negligible Sediment Transport	11,564	210	27,825	913

The area of potential suitable spawning habitat changes greatly between impounded and unimpounded conditions. There are 226 and 3,521 acres of potential suitable habitat for the impounded and unimpounded conditions, respectively (Table 9-5). When the areas that meet depth and velocity criteria, but have missing substrate data, are included, the total area of potential spawning habitat is 1.3 percent and 32 percent of the surface area of the river for the impounded and unimpounded rivers, respectively. The area for suitable habitat for the impounded river would decrease if the sediment data were deemed inadequate. This marked difference in areas of potential suitable habitat for the impounded and unimpounded river is demonstrated for an area above Ice Harbor Dam in Figures 9-7 and 9-8. Much of the suitable spawning habitat for the impounded river is located in the dam tailwaters, and the largest of these areas is below Ice Harbor Dam (Figure 9-9).

Table 9-5. Acres of Potential Suitable Fall Chinook Spawning and Rearing Habitat for the 50 Percent Exceedance-flow for the Impounded and Unimpounded River

Habitats	Impounded (acres)	Unimpounded (acres)
Potential Suitable Spawning Habitat	226	3,521
Potential Possible Spawning Habitat (depth and velocity criteria met, but substrate unknown)	176	1,396
Unsuitable Spawning Habitat	32,177	10,392
Potential Suitable Rearing Habitat	652	889

In addition to spawning habitat potential for fall chinook salmon, the availability and suitability of rearing habitat are critical factors. The rearing habitat criteria is much more restrictive than spawning habitat criteria, and requires that depths are between .3 and 5.3 feet, velocities are less than 4 feet per second, and they must be located within 81.7 feet from shore. This narrow range of depths is adequately resolved within the 1934 channel, but not for the narrow margins near



Above Ice Harbor Dam

Fall Chinook Spawning Habitat Suitability for the Impounded River
for the 50 Percent Exceedance Flow 31710 cfs

Unsuitable Habitat

Unknown (Velocity and Depth Criteria
met, but Substrate Unknown)

Suitable Habitat

North

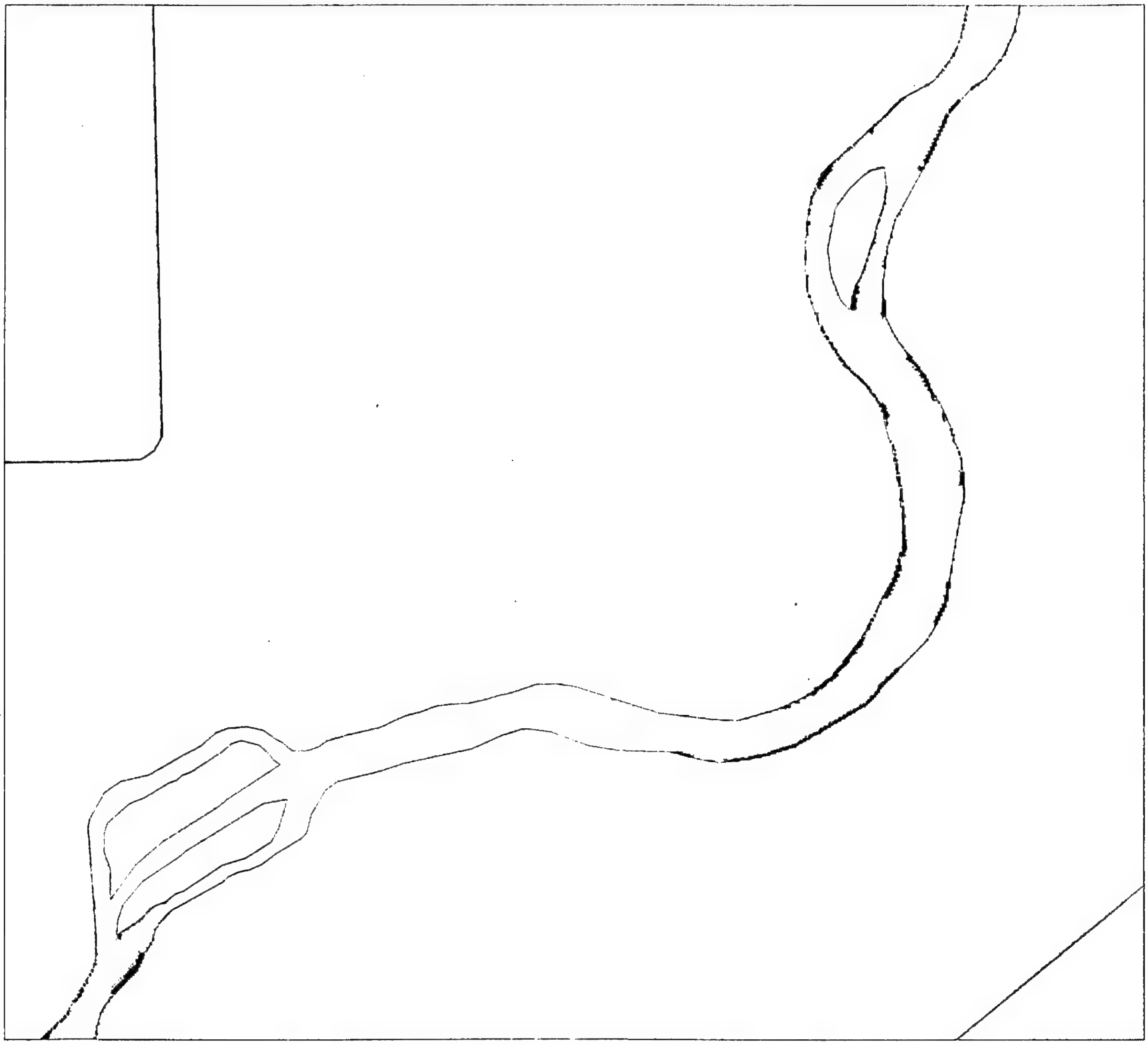
0 1000 2000 3000 4000
Feet

Figure 9-7. Suitable Fall Chinook Spawning Habitats Above Ice Harbor Dam for the Impounded River

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 17, 1999

shorelines for the impounded river. In addition, grid spacing within the numerical model has a nearshore spacing of nodes of about 40 feet, with nodes spaced about 80 to 90 feet in the cross-stream, and about 200 feet in the downstream direction. Consequently, the resulting difference in area of potential suitable rearing habitat of 652 and 89 acres (see Table 9-5, and Figures 9-10 and 9-11 for the impounded and unimpounded rivers) should be viewed with caution. This difference in suitable rearing habitat is supported qualitatively by the difference in shoreline length of 285 and 306 miles (for the impounded and unimpounded rivers, respectively). This increase is the result of increased shoreline complexity with lower water levels and the emergence of midstream islands and bars.



Above Ice Harbor Dam

Fall Chinook Rearing Habitat Suitability for the Unimpounded River
for the 50 Percent Exceedance Flow 31710 cfs

Unsuitable Habitat

Suitable Habitat

North

0 1000 2000 3000 4000
Feet

Figure 9-8. Habitat Suitability for Fall Chinook Spawning Habitats Above Ice Harbor Dam for the Unimpounded River

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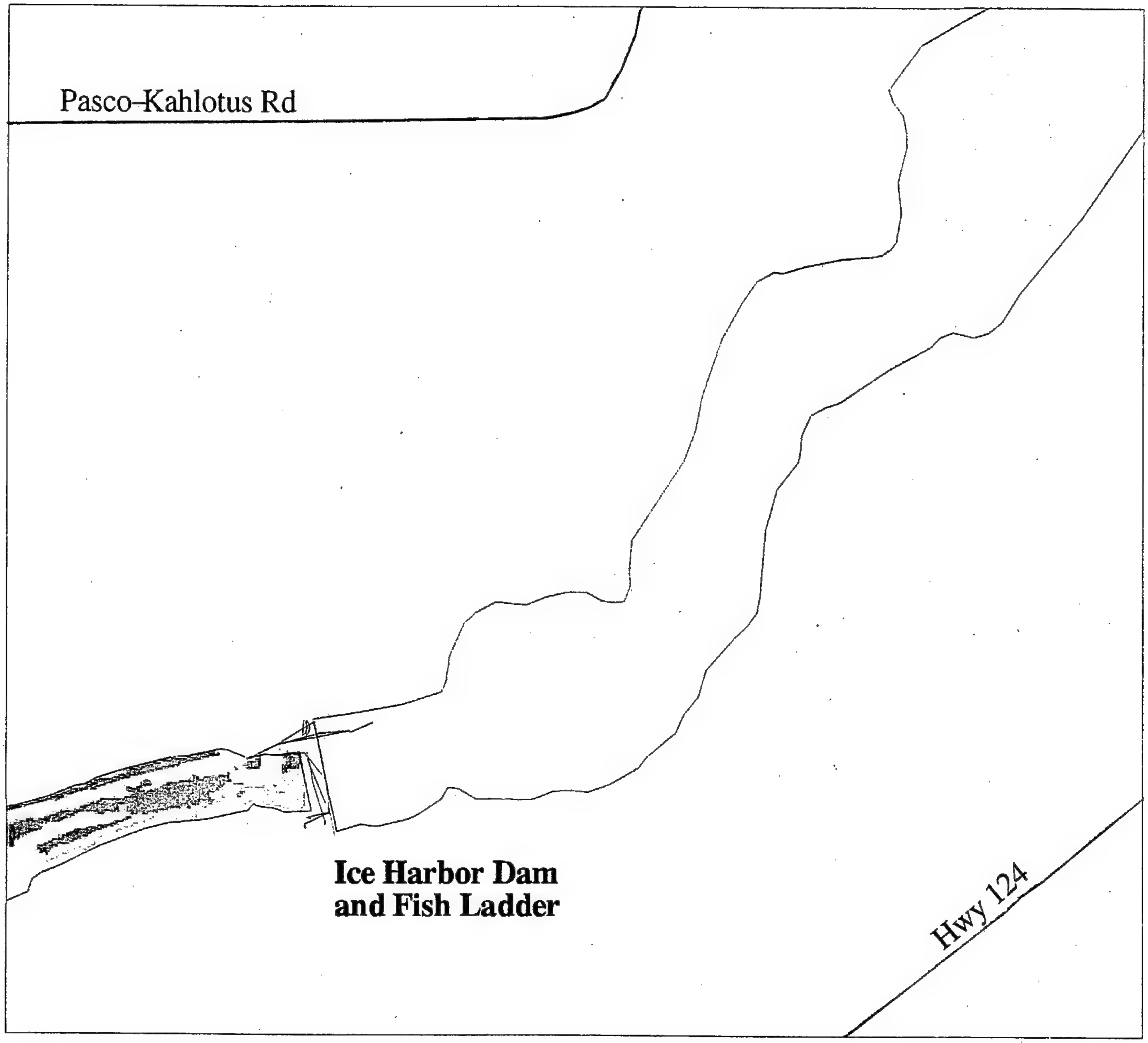
MAP REVISED: August 20, 1998



Ice Harbor Dam

Fall Chinook Spawning Habitat Suitability for the Impounded River
for the 50 Percent Exceedance Flow 31710 cfs

Unsuitable Habitat

Unknown (Velocity and Depth Criteria
met, but Substrate Unknown)

Suitable Habitat

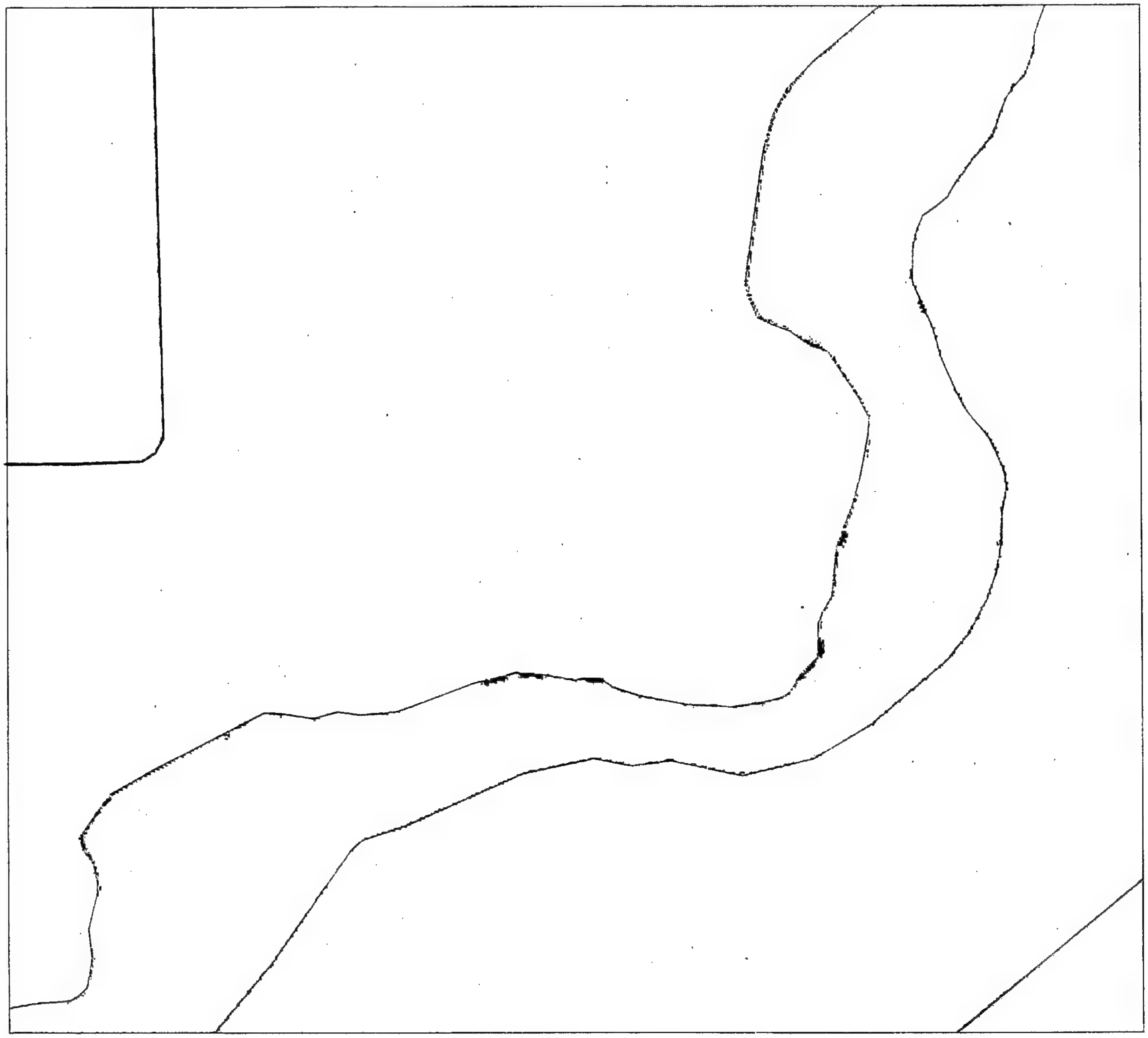
North

0 1000 2000 3000 4000
Feet

Figure 9-9. Potential Habitat Suitability for Fall Chinook Spawning Habitats Near Ice Harbor Dam for the Impounded River

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 17, 1999



Above Ice Harbor Dam

Fall Chinook Rearing Habitat Suitability for the Unimpounded River for the 50 Percent Exceedance Flow 31710 cfs

Figure 9-10. Potential Habitat Suitability for Fall Chinook Rearing Habitats Above Ice Harbor Dam for the Impounded River

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 20, 1999

Above Ice Harbor Dam

Fall Chinook Spawning Habitat Suitability for the Unimpounded River for the 50 Percent Exceedance Flow 31710 cfs

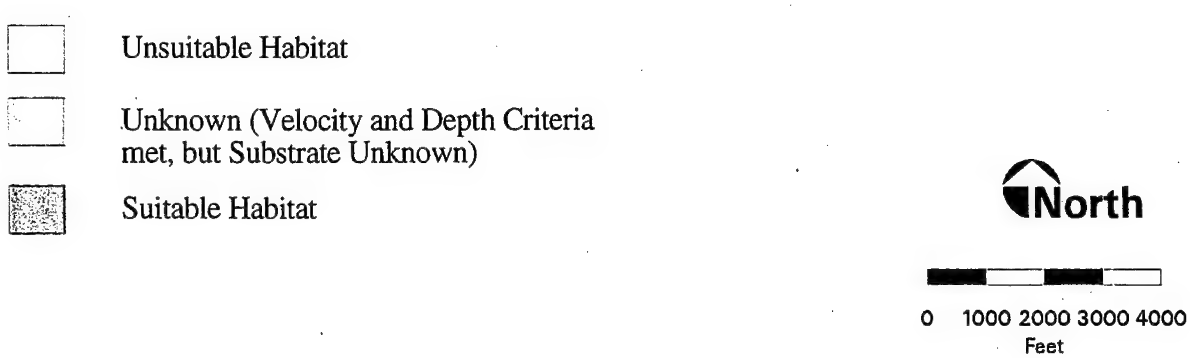


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Figure 9-11. Potential Habitat Suitability for Fall Chinook Rearing Habitats Above Ice Harbor Dam for the Unimpounded River

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MAP REVISED: August 17, 1999

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10. Conclusions and Recommendations

The results of the hydraulic simulations showed that, for the 50 percent exceedance flow (31,710 cfs), the natural river conditions are characterized by a wider range of depth-averaged velocities. For impounded conditions, the majority of river area had velocities less than 2 feet per second. By comparison, the natural river condition shows that most of the velocities are in the range of 1 to 8 feet per second. The natural river conditions case also shows that velocities will be more evenly distributed over that range.

Based on critical velocity criteria, simulations for the 50 percent exceedance flow for impounded conditions showed that mainly sediments finer than a medium sand (0.25-millimeter diameter) would be mobilized or remain in transport. In the natural river case, the same flow would mobilize medium (16 millimeters) to coarse gravel (64 millimeters) or finer materials over most of the river channel. Thus, for typical flow conditions, most of the fine sediments that have been deposited in the lower Snake River reservoirs will be remobilized and transported downstream. The dominance of coarse material is consistent with current observations of substrate composition in the areas immediately downstream of the dams.

Because the lower Snake River hydrograph is affected by water and land management practices throughout the watershed, and is controlled by upstream dams, it is certain that the river channel will not be restored to its pristine pre-development condition by breaching the four lower Snake River dams. Exactly how the resultant channel bed would differ from the original channel bed is unknown. Recent research on gravel-bedded streams indicates that the bed shear stress may have to be three times higher to initiate movement in a substrate composed of coarse materials interlaced with fine sediments, as compared to the uniform bed criteria. The potential decreased mobility of the coarse materials (larger than fine gravel) was examined using a velocity criteria 1.5 times higher than the uniform criteria. Under those conditions, 10 percent exceedance (111,500 cfs) flows may be required to mobilize the same area of coarse materials, as was the case using the uniform criteria at the 50 percent (31,170 cfs) exceedance flow.

Additional information on the evolution of the channel bed would be useful to understand the dynamics of the transition between impounded to natural river conditions. Such simulations would also be useful for designing a field program to monitor and evaluate river conditions if the dams were breached. As stated in the introduction, such simulations would require additional data that would include bathymetric surveys, measurements of sediment grain size distributions in the channel bed, bed sediment depth, transport properties for cohesive sediments, and tributary sediment loads.

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12. Glossary

Alluvial river: A river whose bed and banks are adjustable by current fluvial processes.

Armoring: The process of progressive coarsening of the bed layer by removal of fine particles until the bed becomes resistant to scour.

Bankfull channel: The terminus of the actively used channel and beginning of floodplain in an alluvial river.

Bankfull discharge: The discharge corresponding to the bankfull channel.

Bed load: Material moving on or near the river bed by rolling, sliding, or jumping (saltation). Bed load particles are in constant or frequent contact with the river bed.

Boundary conditions: Definition or statement of conditions or phenomena at the boundaries of an area being modeled; e.g., water surface elevations, flows, sediment concentrations, etc.

Boundary roughness: The roughness of the bed and banks of a river.

Boundary shear stress: Force per unit area exerted on the channel bed by a given flow; largely responsible for mobilizing the bed surface and transporting sediment.

Channel morphology: The shape, size, form, and particle size of a channel created by the interaction of fluvial, biological, and geomorphic processes.

Colluvial river: A river whose bed and banks are comprised of material deposited by forces other than its current flow regime (e.g., mass wasting, glacial deposits).

Critical shear stress: The shear stress (frictional force per unit area) at which bed particles are just able to move, and entrainment is initiated.

Cross section: A profile across a river channel perpendicular to the direction of water flow.

Fluvial processes: Processes associated with the work of streams and rivers in the shaping of landforms.

Geomorphic: Of or resembling the earth, its shape, or surface configuration.

Hydraulic geometry: The relationship of channel width, depth, velocity, and cross-sectional area as a function of discharge.

Hydrodynamic model: The mathematical computation of hydraulic characteristics (e.g., depth (water surface elevation), velocity, slope) of a river as a function of discharge.

Lithology: The gross physical character of a rock or rock formation.

Physiography: Features of the earth's surface, including topography, elevation, aspect, slope, and climate.

Planform: The shape, size, and dimensions of a channel and overbank features as viewed from directly above.

Redd: A fish nest constructed for containing eggs, usually referring to one constructed by a salmon or trout.

Steady state model: Model in which the variables being investigated do not change with time.

Thalweg: An imaginary longitudinal line corresponding to the deepest part of a river channel; usually estimated from a continuous series of cross sections along a river

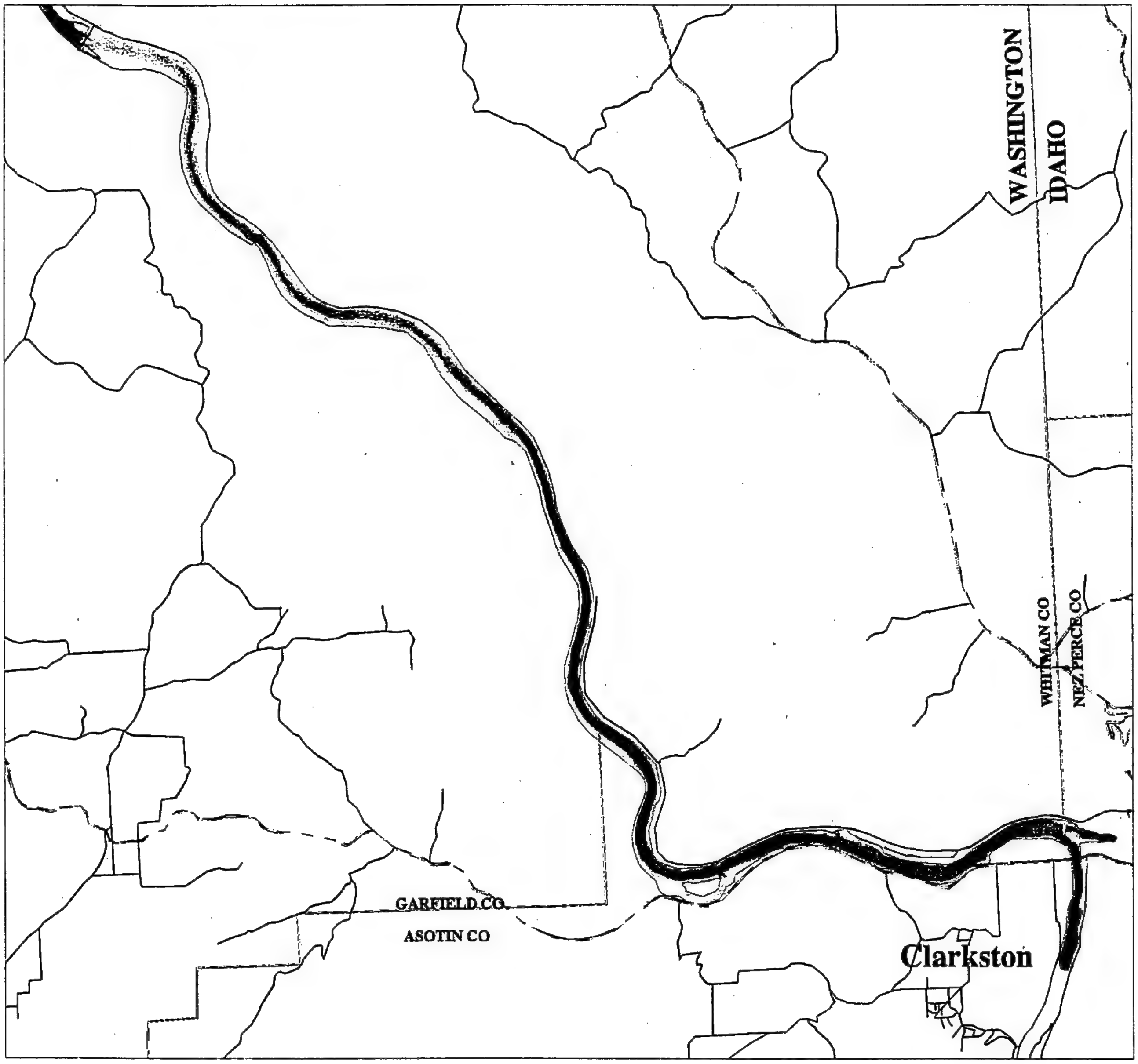
ω: Stream power per unit bed area

Annex A
The 10 Percent Exceedance-flows

ANNEX A
THE 10 PERCENT EXCEEDANCE-FLOWS

The figures in this section are organized as follows:

- Reach scale maps of simulated velocity distribution for each existing pool, starting upstream near the confluence with the Clearwater River. The impounded river map is Figure A-1. The unimpounded river map is Figure A-2.
- A large-scale velocity comparison map for the 10 percent exceedance-flow near the Lower Granite Dam is shown in Figure A-3.
- Large-scale 10 percent exceedance-flow velocities for the unimpounded river and historic observations of dominant substrate size are shown in Figure A-4.
- The full set of figures for the entire lower Snake River can be viewed electronically on the Walla Walla District home page (http://www.nww.usace.army.mil).



Lower Granite Reservoir

Velocity Distribution of the Impounded River
for the 10 Percent Exceedance Flow 111500 cfs

Velocity (ft/s) and Mobilized Substrate

- 9.0 Cobbles (64mm)
- 7.3 Very Coarse Gravel (32mm)
- 5.0 Coarse Gravel (16mm)
- 3.2 Medium Gravel (8mm)
- 1.3 Very Fine Gravel and Coarse Sand (1-2 mm)
- 0.6 Fine Sand (.125mm)
- 0

North

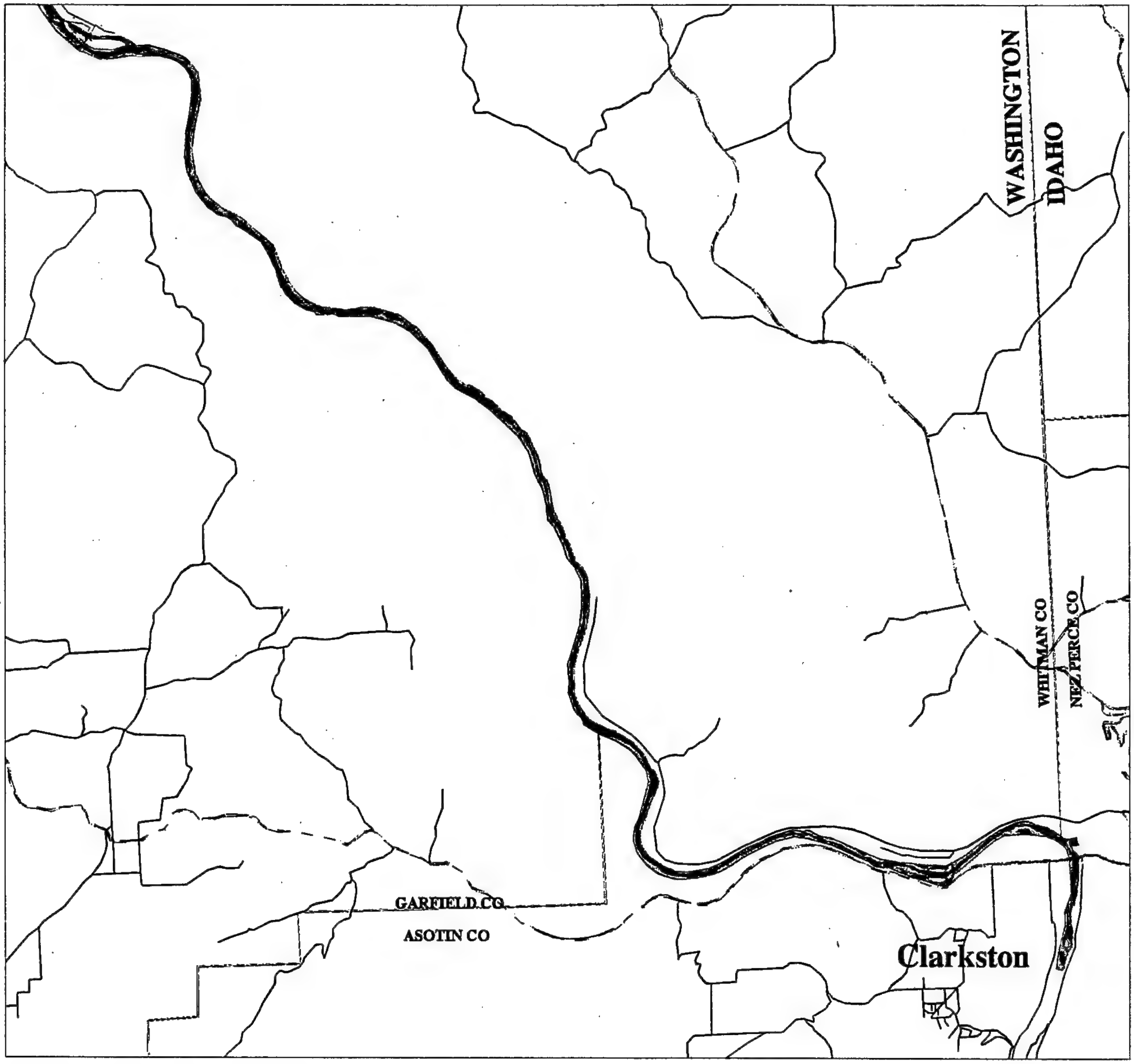
0 2 4 6 8 10
Kilometers

0 1 2 3 4 5 6
Miles

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure A-1. Modeled 10 Percent Exceedance-flow Velocity Distribution for the Lower Granite Reservoir



Lower Granite Reservoir

Velocity Distribution of the Unimpounded River
for the 10 Percent Exceedance Flow 111500 cfs

Velocity (ft/s) and Mobilized Substrate

9.0	Cobbles (64mm)
7.3	Very Coarse Gravel (32mm)
5.0	Coarse Gravel (16mm)
3.2	Medium Gravel (8mm)
1.3	Very Fine Gravel and Coarse Sand (1-2 mm)
0.6	Fine Sand (.125mm)
0	

North

0 2 4 6 8 10
Kilometers

0 1 2 3 4 5 6
Miles

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure A-2. Modeled Unimpounded River 10 Percent Exceedance-flow Velocity Distribution for the Lower Granite Reservoir

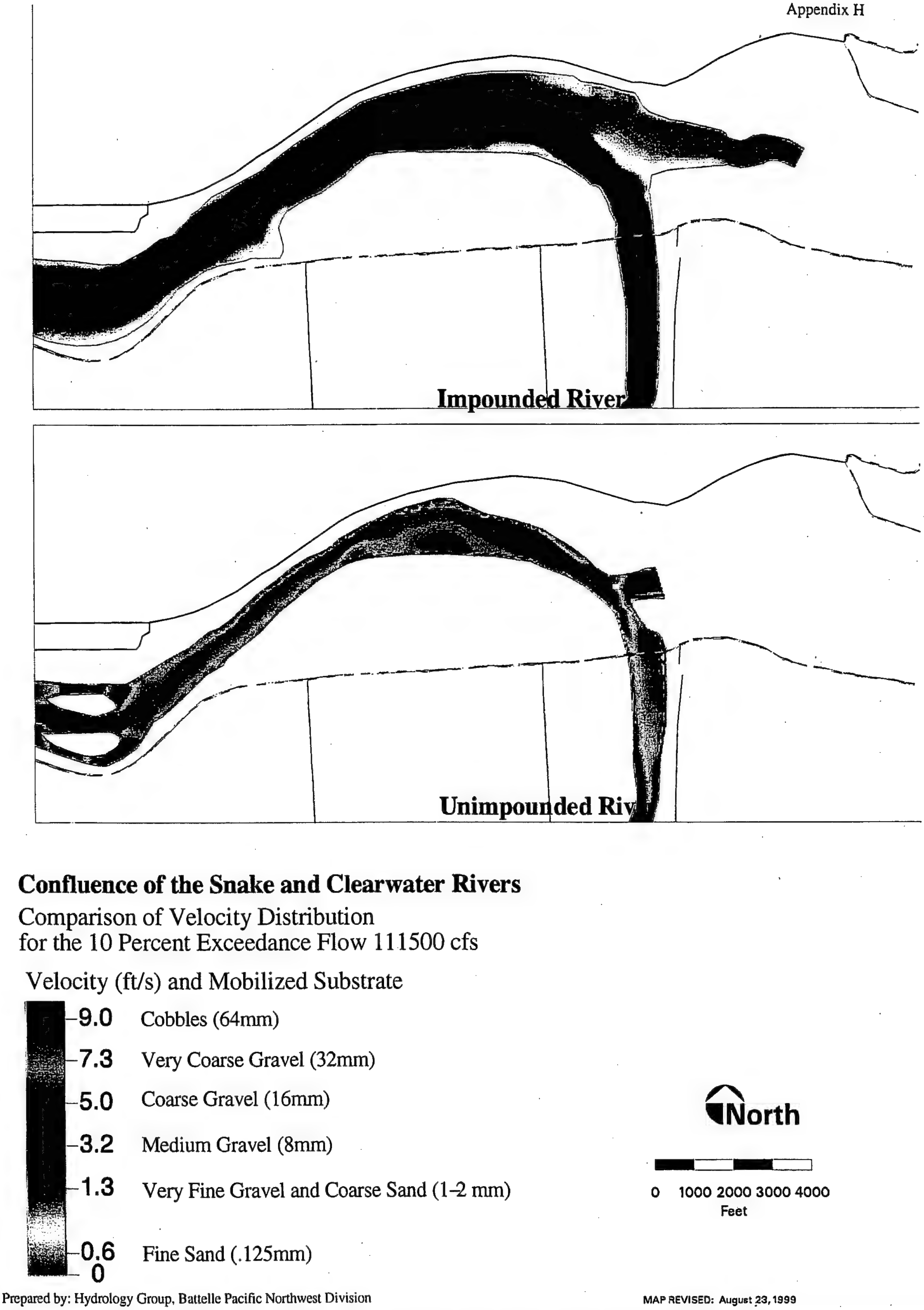
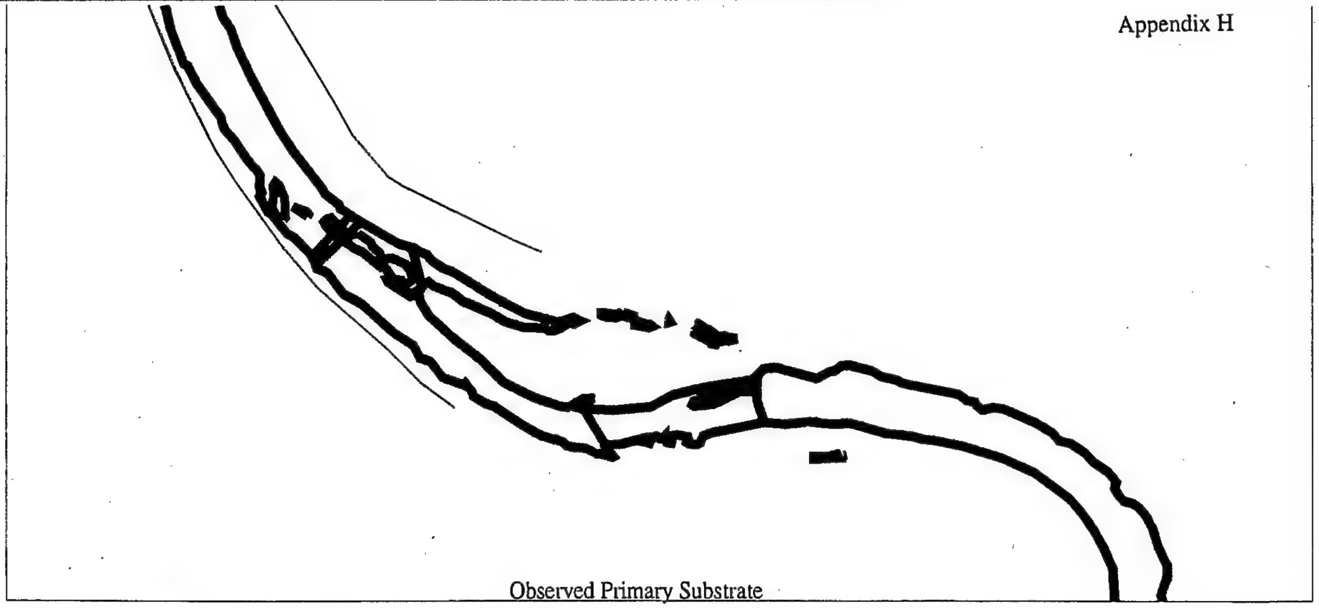
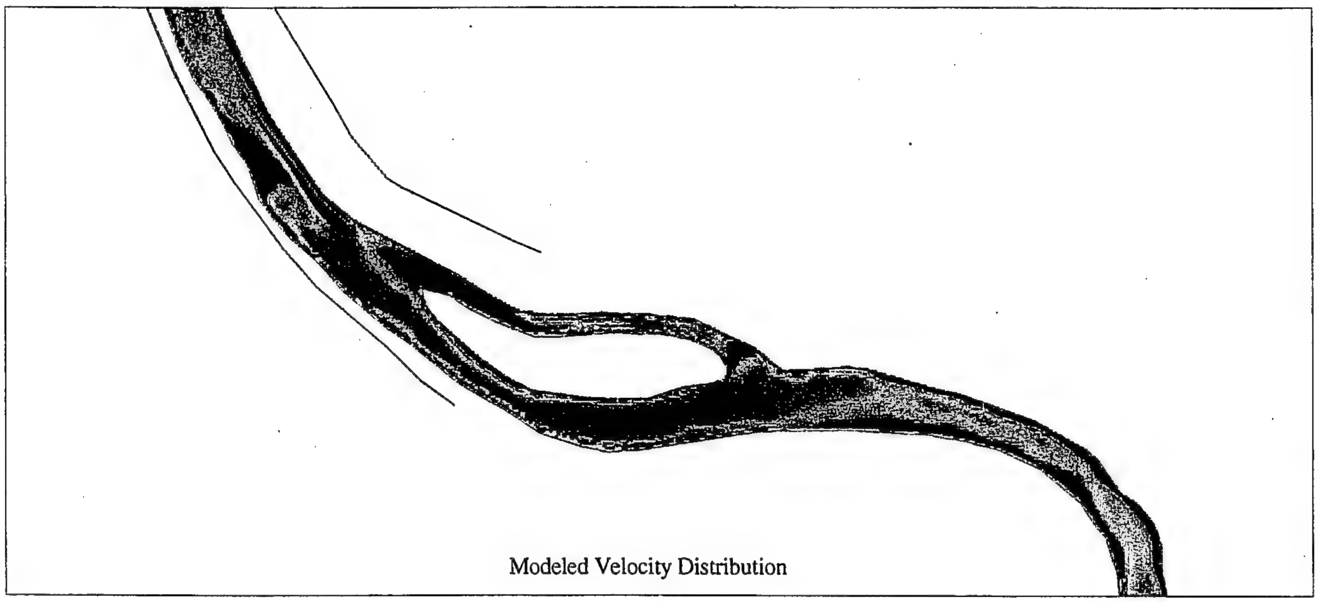


Figure A-3. Comparison of the 10 Percent Exceedance-flow Velocity Distribution near the Confluence of the Snake and Clearwater Rivers for the Full-pool and Unimpounded River





Near Lower Granite Dam

Comparison of Velocity Distribution for the Unimpounded River 10 Percent Exceedance Flow 111500 cfs and Historic Observation of Predominant Sediment Size

Velocity (ft/s) and Mobilized Substrate

- 9.0 Cobbles (64mm)
- 7.3 Very Coarse Gravel (32mm)
- 5.0 Coarse Gravel (16mm)
- 3.2 Medium Gravel (8mm)
- 1.3 Very Fine Gravel and Coarse Sand (1-2 mm)
- 0.6 Fine Sand (.125mm)
- 0

Bedrock and Boulders

Cobbles

Gravel

Sand

Silt

North

0 1000 2000 3000 4000

Feet

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure A-4. Comparison of the 10 Percent Exceedance-flow Velocity Distribution and Historic Dominant Substrate near Lower Granite Dam for the Unimpounded River Simulations

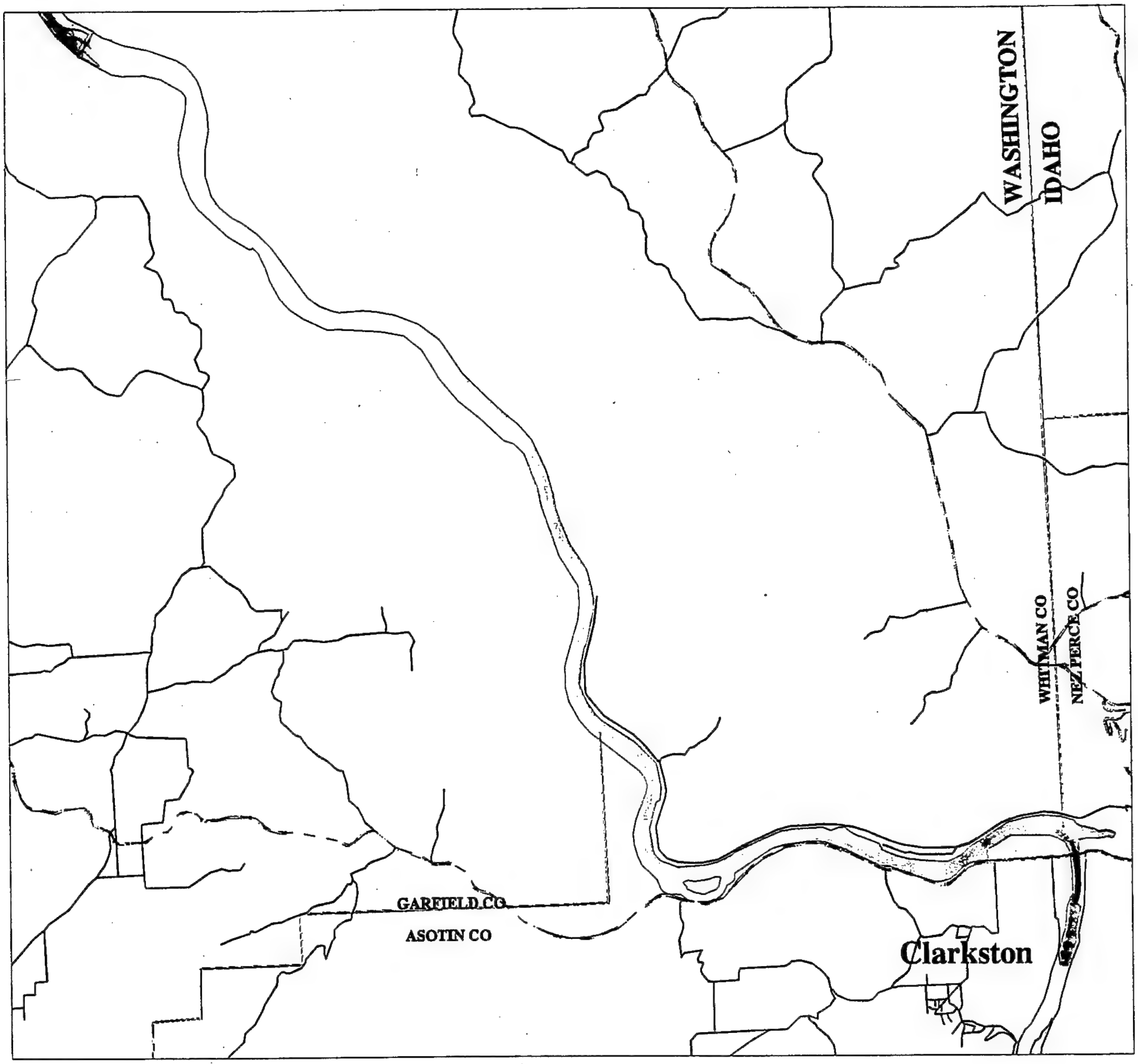
Annex B

The 50 Percent Exceedance-flows

ANNEX B
THE 50 PERCENT EXCEEDANCE-FLOWS

The figures in this section are organized as follows:

- Reach scale maps of simulated velocity distribution for each existing pool, beginning upstream near the confluence with the Clearwater River. The impounded river map is Figure B-1, followed by the unimpounded river map, Figure B-2.
- A large-scale velocity comparison map for the 50 percent exceedance-flow near the Lower Granite Dam is shown in Figure B-3.
- A potential spawning habitat suitability map for the 50 percent exceedance-flow near the confluence of the Snake and Clearwater Rivers is shown in Figure B-4.
- A potential rearing habitat suitability maps for the 50 percent exceedance-flow near the confluence of the Snake and Clearwater Rivers is shown in Figure B-5.
- The full set of figures for the entire lower Snake River can be viewed electronically on the Walla Walla District home page (http://www.nww.usace.army.mil).

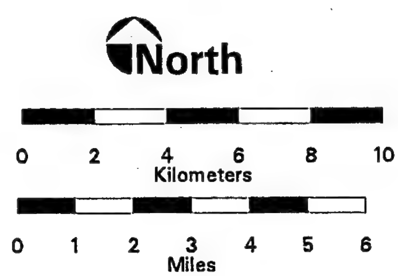


Lower Granite Reservoir

Velocity Distribution of the Impounded River
for the 50 Percent Exceedance Flow 31710 cfs

Velocity (ft/s) and Mobilized Substrate

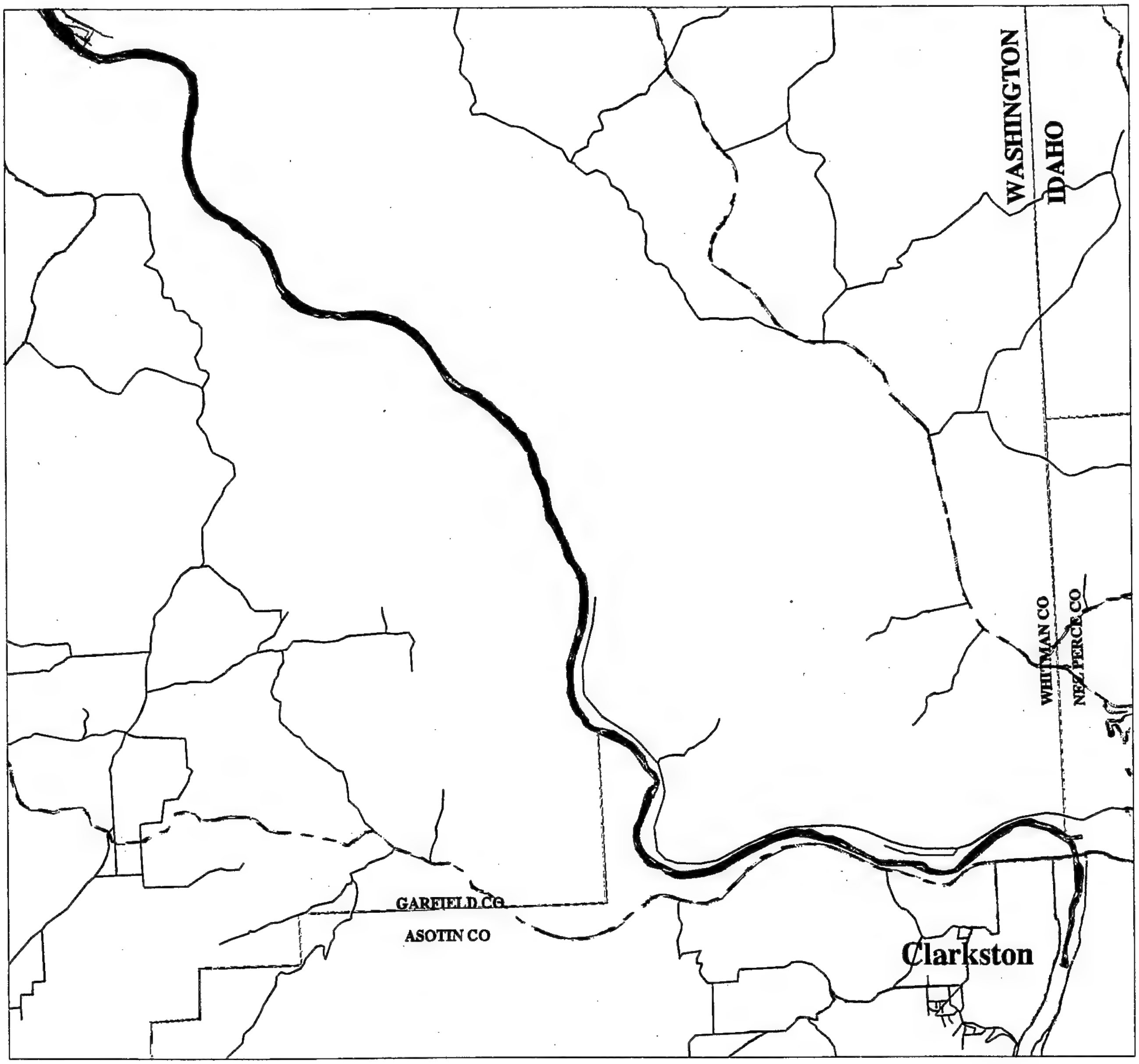
9.0	Cobbles (64mm)
7.3	Very Coarse Gravel (32mm)
5.0	Coarse Gravel (16mm)
3.2	Medium Gravel (8mm)
1.3	Very Fine Gravel and Coarse Sand (1–2 mm)
0.6	Fine Sand (.125mm)
0	



Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure B-1. Modeled 50 Percent Exceedance-flow Velocity Distribution for the Lower Granite Reservoir



Lower Granite Reservoir

Velocity Distribution of the Unimpounded River
for the 50 Percent Exceedance Flow 31710 cfs

Velocity (ft/s) and Mobilized Substrate

9.0	Cobbles (64mm)
7.3	Very Coarse Gravel (32mm)
5.0	Coarse Gravel (16mm)
3.2	Medium Gravel (8mm)
1.3	Very Fine Gravel and Coarse Sand (1-2 mm)
0.6	Fine Sand (.125mm)
0	

North

0 2 4 6 8 10
Kilometers

0 1 2 3 4 5 6
Miles

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure B-2. Modeled 50 Percent Exceedance-flow Velocity Distribution for the Lower Granite Reservoir for the Unimpounded River

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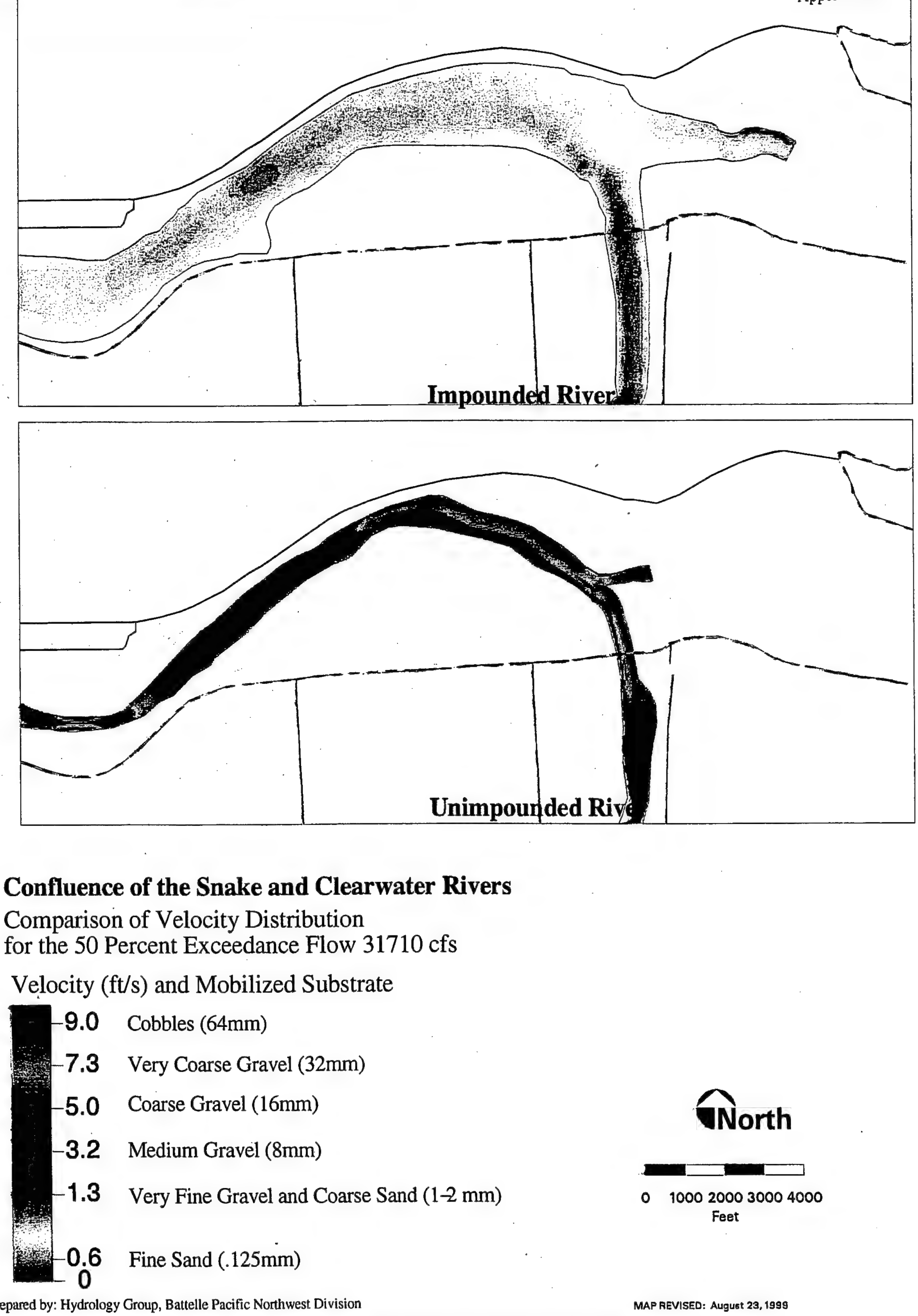
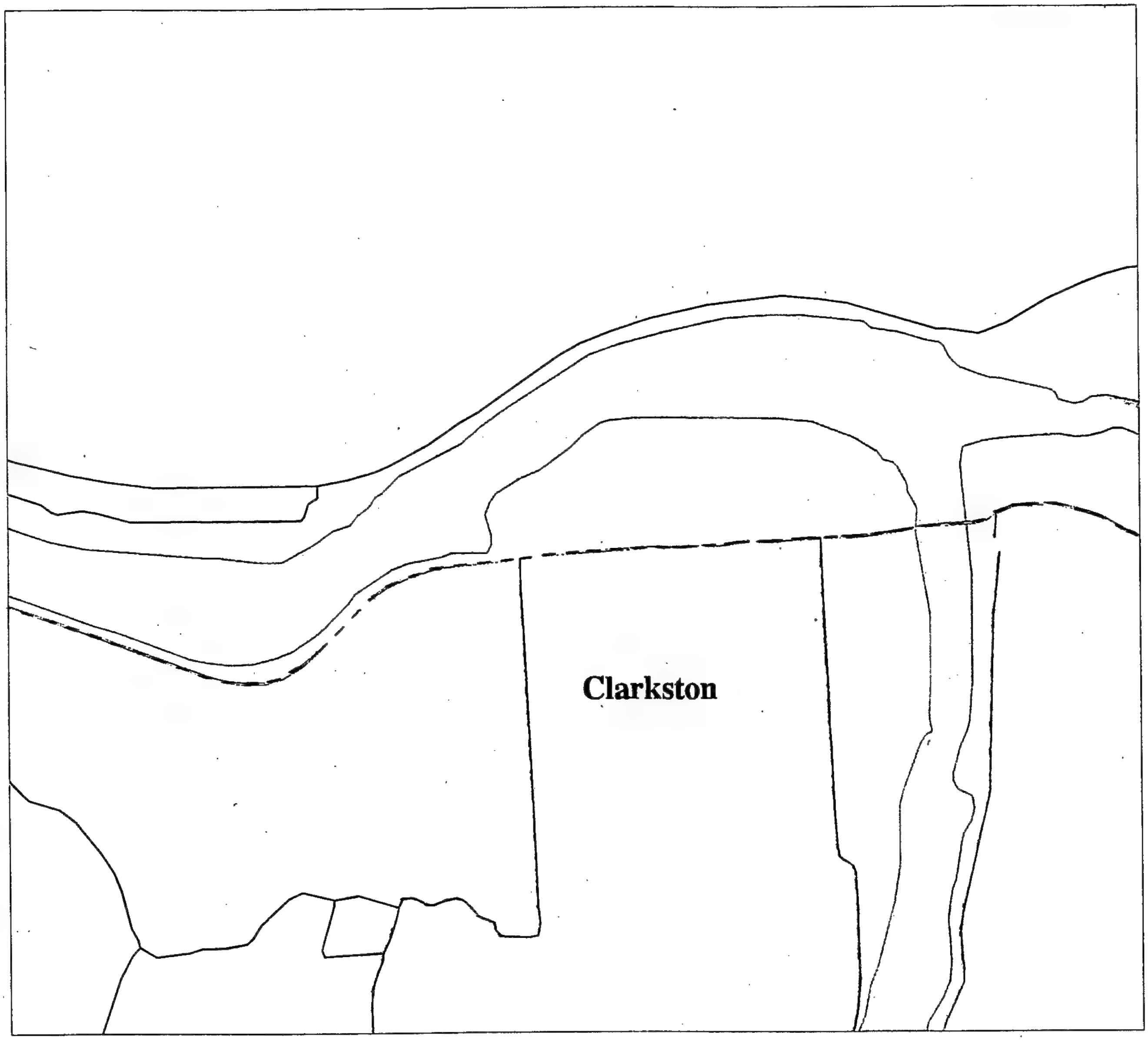


Figure B-3. Comparison of the 50 Percent Exceedance-flow Velocity Distribution near the Confluence of the Snake and Clearwater Rivers for the Full-pool and Unimpounded River



Confluence of the Snake and Clearwater Rivers

Fall Chinook Spawning Habitat Suitability for the Impounded River
for the 50 Percent Exceedance Flow 31710 cfs

Unsuitable Habitat

Unknown (Velocity and Depth Criteria
met, but Substrate Unknown)

Suitable Habitat

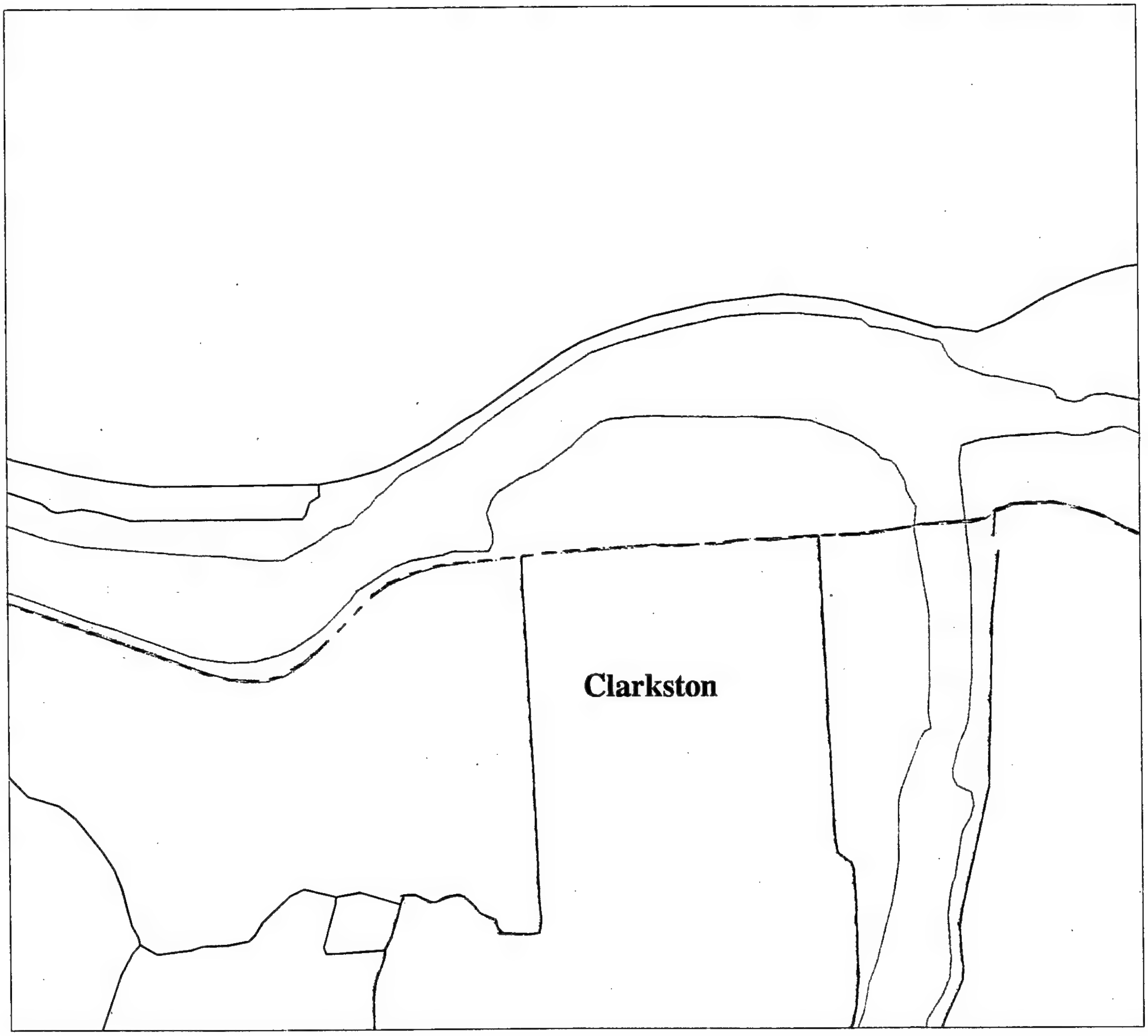
North

0 1000 2000 3000 4000
Feet

Figure B-4. Potential Habitat Suitability for Fall Chinook Spawning Habitats near the Confluence of the Clearwater and Snake Rivers for the Impounded River

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 17, 1999



Confluence of the Snake and Clearwater Rivers

Fall Chinook Rearing Habitat Suitability for the Unimpounded River for the 50 Percent Exceedance Flow 31710 cfs

Figure B-5. Potential Habitat Suitability for Fall Chinook Rearing Habitats near the Confluence of the Clearwater and Snake Rivers for the Unimpounded River

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 20, 1999

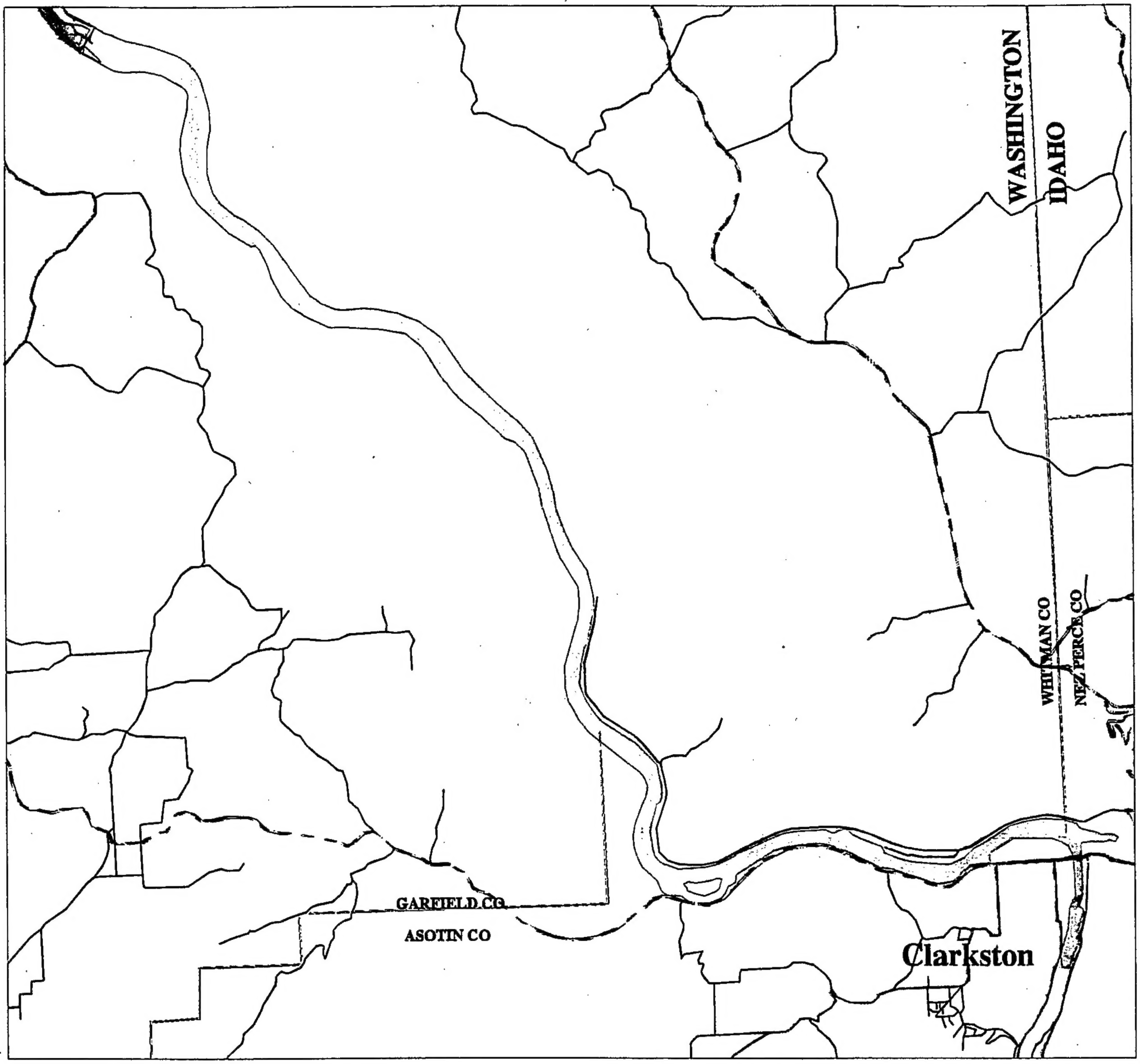
Annex C

The 80 Percent Exceedance-flows

ANNEX C
THE 80 PERCENT EXCEEDANCE-FLOWS

The figures in this section are organized as follows:

- Reach scale maps of simulated velocity distribution for each existing pool, beginning upstream near the confluence with the Clearwater River. The impounded river map is Figure C-1, followed by the unimpounded river map (Figure C-2).
- Large-scale velocity comparison maps for the 80 percent exceedance-flow near the confluence of the Snake and Clearwater Rivers are shown in Figure C-3.
- The full set of figures for the entire lower Snake River can be viewed electronically on the Walla Walla District home page (http://www.nww.usace.army.mil).



Lower Granite Reservoir

Velocity Distribution of the Impounded River
for the 80 Percent Exceedance Flow 19900 cfs

Velocity (ft/s) and Mobilized Substrate

-9.0 Cobbles (64mm)
-7.3 Very Coarse Gravel (32mm)
-5.0 Coarse Gravel (16mm)
-3.2 Medium Gravel (8mm)
-1.3 Very Fine Gravel and Coarse Sand (1-2 mm)
-0.6 Fine Sand (.125mm)
0

North

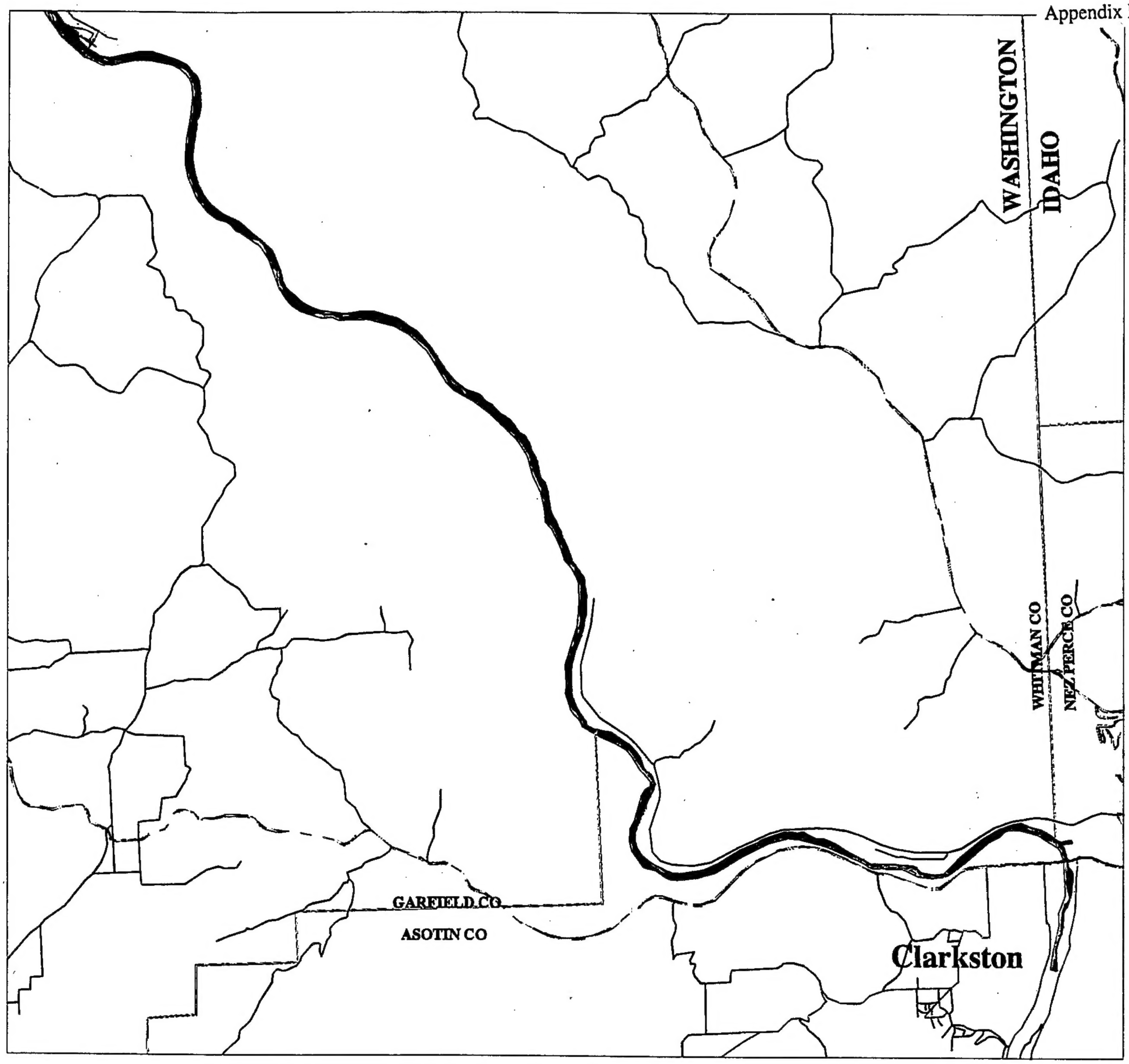
0 2 4 6 8 10
Kilometers

0 1 2 3 4 5 6
Miles

Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

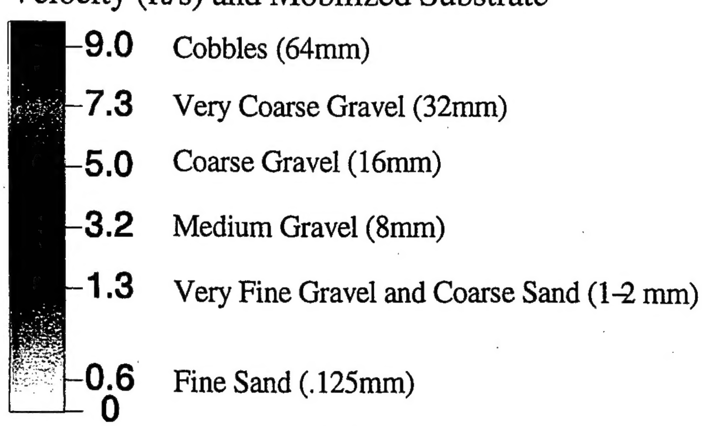
Figure C-1. Modeled 80 Percent Exceedance-flow Velocity Distribution for the Lower Granite Reservoir

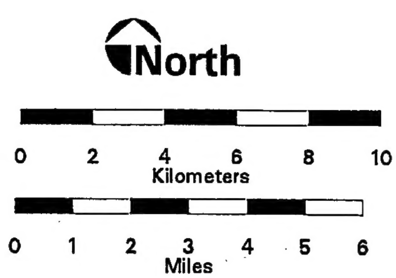


Lower Granite Reservoir

Velocity Distribution of the Unimpounded River
for the 80 Percent Exceedance Flow 19900 cfs

Velocity (ft/s) and Mobilized Substrate





Prepared by: Hydrology Group, Battelle Pacific Northwest Division

MAP REVISED: August 23, 1999

Figure C-2. Modeled 80 Percent Exceedance-flow Velocity Distribution near the Lower Granite Reservoir for the Unimpounded River

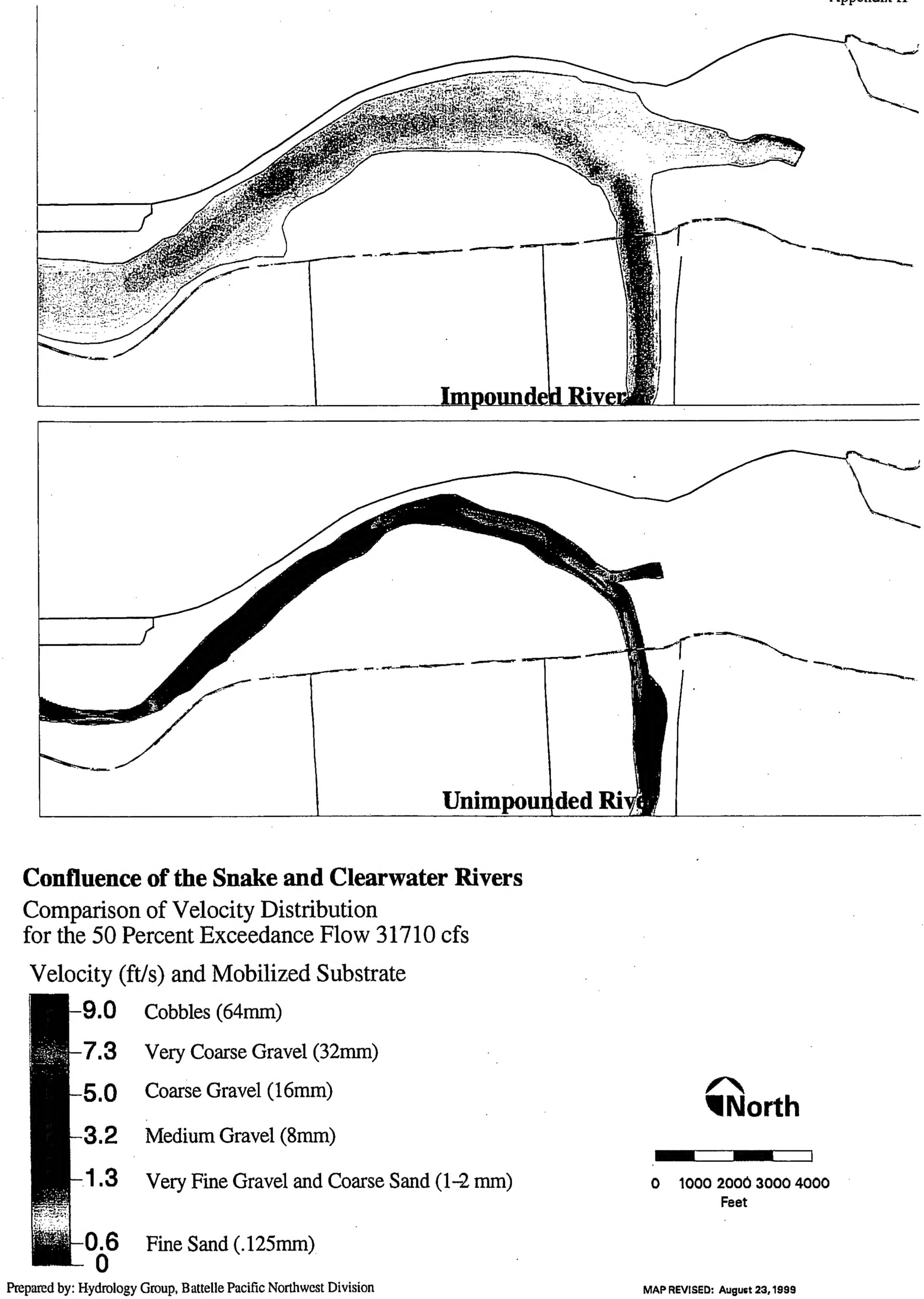


Figure C-3. Comparison of the 80 Percent Exceedance-flow Velocity Distribution near the Confluence of the Snake and Clearwater Rivers